



# ENGINEERING LAMINATES





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EDITED BY

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# Preface

Laminates of engineering significance form the subject matter of this book. This includes composites of essentially all one class of material such as wood or metal, composites of several widely different materials such as plastic or rubber and fabric, composites essentially the same density throughout, and composites of lightweight cores and denser stronger skins commonly referred to as sandwich structures. A given material is included in this book if it is useful from an engineering standpoint and if it is significantly different in its composite properties or use from its constituents. Decorative laminates, of which there are many, are excluded. Laminates in which the surface material is essentially only a protective coating are also excluded. Plated, galvanized, and similar thinly coated materials are, consequently, ruled out. Evidently, the dividing line between coated materials and laminated materials is not a sharp one, and it may be questioned whether some of the materials excluded might not properly have been included, and whether some materials included might not be considered to fall in the class of coatings. Unquestionably, in many laminates one of the principal functions of the surface materials is protection.

In the arrangement of this book, the first two chapters and the last chapter are general in content. The first chapter is devoted to a discussion of the general mathematical theory or applied mechanics of laminates. This is followed by a chapter devoted to adhesives because adhesives play an important part in many laminates, and improved adhesives have made possible the widespread use of some of them. Following these first two chapters are those devoted to specific classes of laminates. First come chapters devoted to laminates of essentially the same materials such as wood and metal. These are followed by chapters devoted to laminates composed of several different materials. Last comes a general chapter devoted to a discussion of methods of forming various laminates and sandwich materials.

Such an arrangement can only be general because composites may be numerous different combinations, and many cannot be neatly classified. In at least two groups—plastics-based and rubber-based laminates—the bulk of the composite may be something other than plastics or rubber. Compreg, for example, is mostly wood. Never-

theless, the plastics or rubber is the bonding or saturating material and permeates the structure.

In a symposium of this kind some overlapping among closely related sections is unavoidable. The various chapters have been carefully edited to avoid as much duplication as possible, but in some instances overlapping material has been left in because of the different points of view expressed by different authors.

Although this book is devoted to laminates, it necessarily includes a good deal of information respecting the properties of the base materials of which the laminates are composed. Furthermore, it discusses subjects which are not peculiar to laminates alone. Thus the chapter on hard surfacing by fusion welding contains a discussion of hardness and abrasion resistance, the section on rubber laminates includes material respecting the various rubbers and their properties, and the various sections dealing with metal-clad laminates include information respecting the corrosion resistance and other properties of the cladding metals.

An attempt has been made throughout to emphasize the engineering properties of the materials. Where the authors have thought it desirable, they have included discussions of manufacturing and fabricating procedures, applications, and economics. In general, however, these discussions are subordinate to the exposition of engineering properties.

The editor extends his sincere thanks to the many individuals who have made this symposium possible. The subject was first suggested by Dr. H. W. Gillette of Battelle Memorial Institute, who pointed out the need for a work of this kind. Mr. E. M. Wise of the International Nickel Company was especially helpful with suggestions respecting the chapters devoted to metallic laminates. In this connection the editor is also indebted to Professors R. S. Williams and V. O. Homerberg of the Massachusetts Institute of Technology. The individual authors have worked hard to prepare their sections, often at considerable personal inconvenience, in time snatched from crowded schedules. The publishers have extended every possible aid in bringing the task to completion. Such virtues as the book may possess should be credited to these individuals. Its faults are those of the editor.

ALBERT G. H. DIETZ

Cambridge, Massachusetts  
February 3, 1949

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## Introduction

Laminated engineering materials are employed in increasing volume and in more and more diverse fields because (1) they combine the properties of their component parts to obtain composite properties which may be new or unique, or (2) they make it easier or less costly

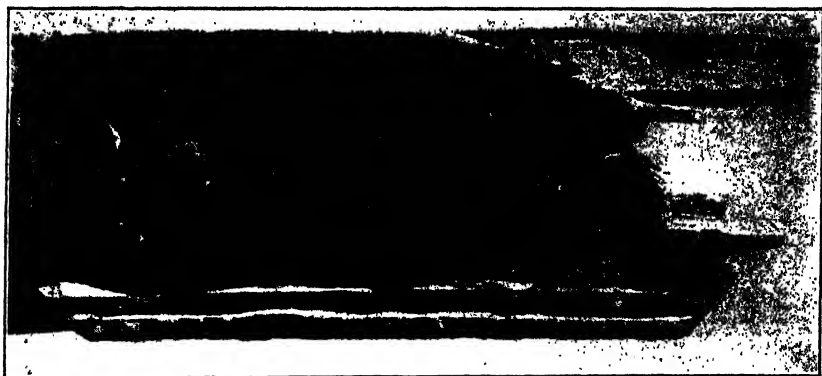


FIG. 1. Fragment of Egyptian Laminated Wood of the Eighteenth Dynasty (about 1500 B.C.) Found at Thebes. Five thin pieces are glued-laminated at the bottom to the heavier piece. A piece of veneer is glued at the top. (Courtesy Metropolitan Museum of Art, New York)

to obtain certain properties than is possible with "solid" materials. The behavior of thermostat metals depends on the combination of dissimilar metals, safety glass owes its value to the combination of quite different materials, structural sandwiches possess high weight-strength ratios, clad metals combine strong or inexpensive cores with highly corrosion-resistant faces, laminated timbers can be made in sizes and shapes unattainable in solid timber, composite decks of timber and concrete combine the wearing qualities and hardness of concrete with the impact strength and resilience of wood, plastics-based and rubber-based laminates combine strength, flexibility, chemical and electrical



properties, and abrasion resistance. The list could be greatly extended.

Laminating, to improve the properties of materials or to combine several materials into one, is not new, but the rapid expansion of the principle into a great variety of different applications is relatively recent. To a large degree, therefore, it represents something new in the field of materials.



FIG. 2. Fifteenth Century German Armor (circa 1475) Showing Structure of Alternating Layers of Steel and Iron. (Courtesy Metropolitan Museum of Art, New York)

Early examples of laminates include glued wood, in the form of parallel-laminated members and plywood, often considered to be quite new. In Fig. 1 is shown a piece of ancient Egyptian laminated wood (now in the possession of The Metropolitan Museum of Art, New York) which was found at Thebes and belongs to the eighteenth dynasty (about 1500 B.C.). At the bottom are five thin pieces glued-laminated to the heavier piece. At the top is a piece of glued veneer. There are extant fragments of laminated wood from a coffin of the third dynasty (2780 B.C.) which antedate by over 1200 years the piece illustrated. The Romans also used plywood for fine furniture. The greatly increased use of plywood and its application to engineering structure is, however, a recent phenomenon, largely made possible by improved synthetic adhesives.

The makers of arms and armor,\* in the Near and Far East as well as in Europe, understood the value of laminated metal. In Fig. 2 is an example of fifteenth century German armor (circa 1475) showing a typical laminated structure of alternating layers of steel and iron.

\*The information concerning armor and swords and the accompanying illustrations were made available by Mr. Stephen V. Grancsay, curator of arms and armor, The Metropolitan Museum of Art, New York. For a more complete description of the Japanese swords, see "Samurai Swords" by Stephen V. Grancsay, *American Collector*, February 1946, p. 6ff.

## Introduction

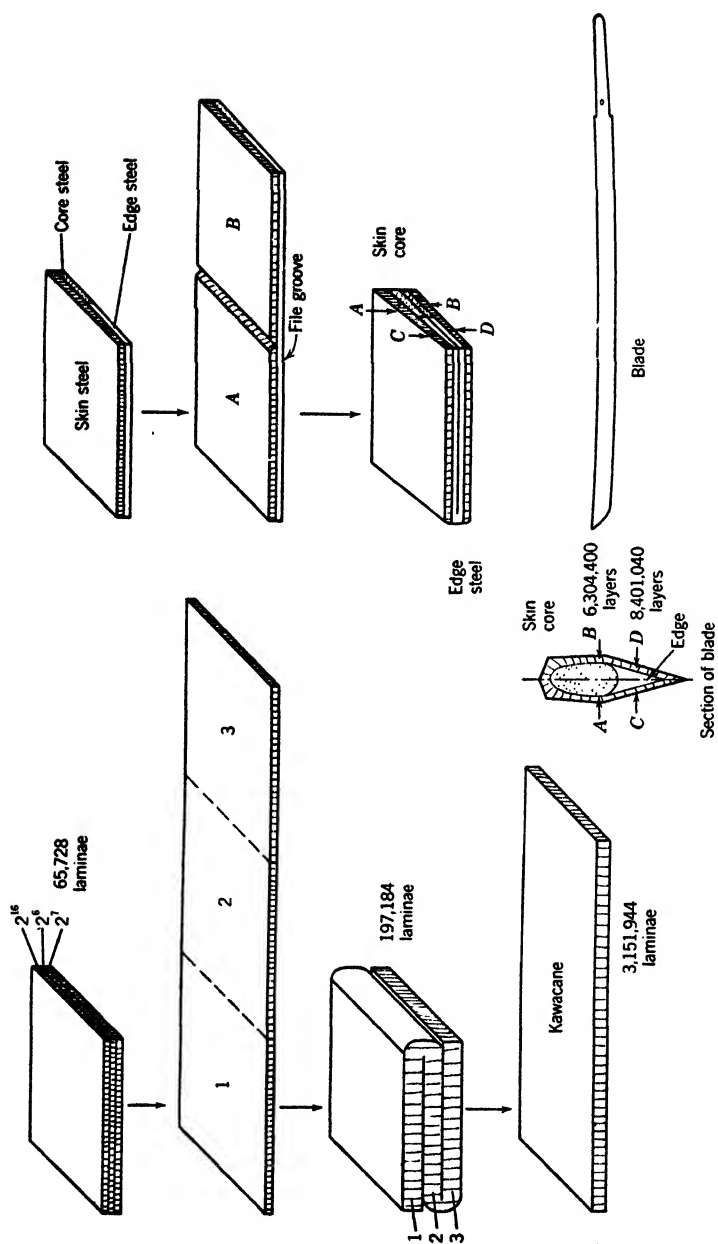
Similarly, in Fig. 3 is a German breastplate (circa 1520) showing the welding of layers of steel and iron.

Outstanding examples of fine craftsmanship in laminated metal are to be found in the famed Damascus swords and in the consummate skill and art of the Japanese swordmaker. The fine Japanese blade first of all combines several different steels or steels and irons to provide an extremely hard and keen edge, while the body of the blade is relatively soft. In one type of compound blade, for example, three types of steel are used, one for the core, a second for the sides or skin (cover steel) and a third for the edge. The edge steel is theoretically folded over 20 times and welded each time by skillful hand forging. It, therefore, consists of  $2^{20}$  or 1,048,576 layers; the core steel is similarly folded 8 times and consists of  $2^8$  or 256 layers. The skin steel is more complex. It is made of three sheets, the first folded 16 times ( $2^{16} = 65,536$  layers), the second folded six times ( $2^6 = 64$  layers), and the third folded seven times ( $2^7 = 128$  layers). These are first hammered into



FIG. 3. German Breastplate (circa 1520) Showing Welding of Layers of Iron and Steel. (Courtesy Metropolitan Museum of Art, New York)

a single sheet of 65,728 layers, then cut into three, placed over each other ( $3 \times 65,728 = 197,184$  layers), and finally folded over four times ( $197,184 \times 2^4 = 3,151,944$  layers). Pieces of core and edge steel are placed side by side and a sheet of skin steel over them. These three are hammer-welded together and are then cut in two and turned over so that the skin steel comes on the two surfaces. This combination is hammered down into a blade in which over 8,000,000 layers have been welded and stretched out at the edge. Special heat treatments finally increase the silicon and carbon content at the edge, which thereby becomes much harder than the rest of the blade. The steps in the process are illustrated in Fig. 4.



Making of skin steel (Kawacane)

Fig. 4. Steps in the Making of a Laminated Japanese Samurai Sword. Left, raking of skin steel. Right, disposition of three types of steel which are forged into blade. (Courtesy American Collector)

Modern engineering laminates, of course, are not made by such painstaking hand processes as are employed in fabricating fine pieces of armor. The basic principles—orientation of structure and strength properties, combinations of hardness, toughness, lightness, strength, durability, and other desirable engineering attributes—are essentially the same. Because no one material is adequate to the task, materials are combined—laminated—to obtain the combined properties or unique new properties necessary to fulfill the requirements of a particular engineering application.

# CHAPTER 1

## The Strength of Laminates and Sandwich Structural Elements

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### INTRODUCTION

In the terminology of this chapter a laminate is a body constructed of several laminas, that is, layers. When one of the three dimensions of the body, namely, its thickness, is small compared to its other two dimensions, the body is called a plate or a shell. The difference between the two terms is that a plate is plane whereas a shell is curved. When two of the dimensions of the body, namely, the cross-sectional dimensions, are small compared to the third, the length, the body is known as a bar, rod, tie, brace, column, strut, or beam. The main difference between the structural elements meant by these six terms is the type of loading to which they are subjected. Their physical appearance is similar, although different cross-sectional shapes are advantageous for different loads. Bar and rod are rather general terms; ties are usually subjected to tension, braces to tension or compression, columns and struts to compression, and beams to bending.

Sandwich construction makes use of that particular type of laminate which consists of thin, strong, and comparatively heavy outer layers, known as faces, and one or more light, thick, and comparatively weak inner layers, designated as the core.

In a laminate the various layers may be made of the same material or of two or more different materials. The mechanical properties of any one layer may be different in different directions as is true, for instance, of wood. Even a steel plate is, as a rule, stronger in tension in the direction in which it was last rolled in the mill than across this direction. Nevertheless, it is customary to consider a steel plate as an isotropic body, that is, one that has the same mechanical properties

in every direction, since the differences in these properties are comparatively small. Such a simplified representation of reality is not permissible in the case of wood whose strength and rigidity are 5 to 50 times greater in the direction of the grain than across it. In theoretical calculations, wood is considered an orthotropic body, that is, one that has three mutually perpendicular principal axes of elasticity. At any point in the timber the principal axes are oriented as the grain and as the tangent and the perpendicular to the year ring in a section of the timber perpendicular to the grain.

Another important group of laminates is made of synthetic resins reinforced with fabric. Here again three principal axes of elasticity can be discerned. Two of them are oriented as the directions of the warp and the filler, and the third is perpendicular to the plane of the former two.

All laminas discussed in this chapter are assumed to be homogeneous. This means that the elastic properties of any portion of the lamina are independent of the location of the portion in the lamina.

The mechanical properties of laminated structural elements depend on the mechanical properties of the individual laminas of which they are made up and on the arrangement of these laminas. An analysis must begin, therefore, with the investigation of the mechanical properties of the homogeneous lamina.

## STRESS AND STRAIN IN A LAMINA

### THE GENERALIZED HOOKE'S LAW

Figure 1-14 represents a small flat rectangular piece cut out of a lamina. On its horizontal edges is acting a tensile stress,  $\sigma_1 = 200$  psi; on its vertical edges a compressive stress,  $\sigma_2 = -150$  psi; and on all the four edges a shear stress,  $\tau = 50$  psi. The lamina is assumed to be orthotropic, and the direction of one principal axis of elasticity is indicated in the figure by the hatching which subtends an angle  $\alpha = 30^\circ$  with the vertical. If the rectangle were cut out of a wooden board, the hatching would indicate the fibers.

It is of interest to determine the changes caused by the stresses in the length of the edges of the small rectangle and the changes in the angles subtended by the edges. These angles are right angles before the application of the loads. The elastic constants needed for such a calculation are, in general, not available in the case of an orthotropic material for an arbitrary direction of the load, but they are known when the loads are applied in the principal directions of elasticity.

For instance, when a tensile stress  $\sigma_L$  is applied in the direction of the grain as shown in Fig. 1-1C, it causes a tensile strain  $\epsilon_L = \sigma_L/E_L$  in its own direction and a compressive strain  $\epsilon_T = -\mu_{LT}\epsilon_L$  in the perpendicular

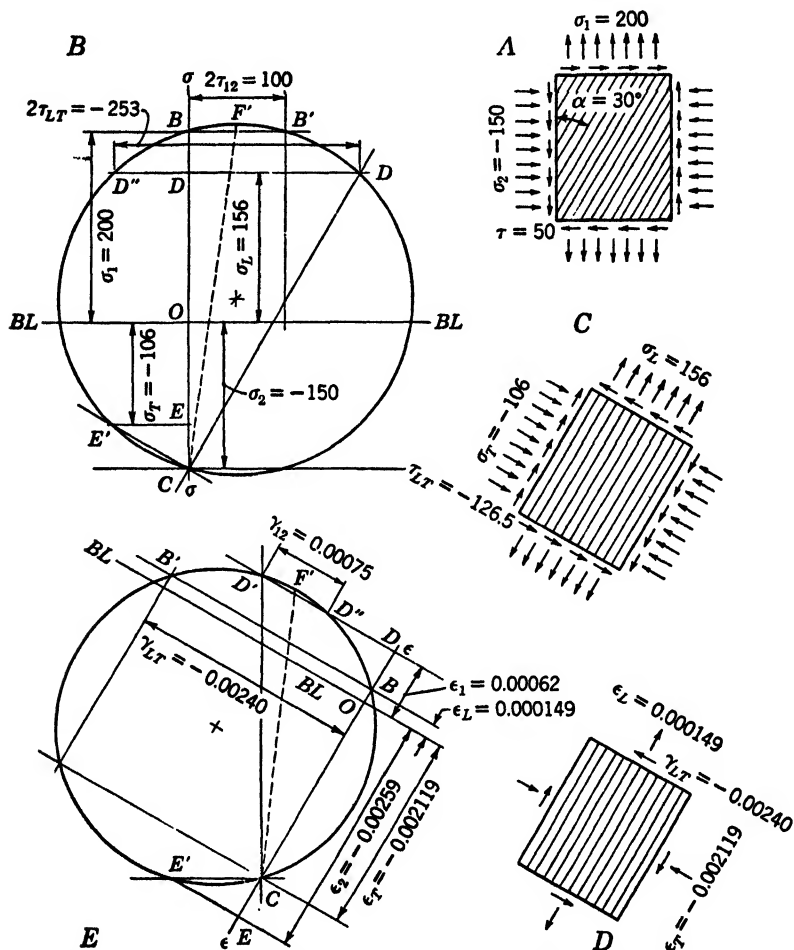


FIG. 1-1. Stress and Strain in an Orthotropic Plate (Spruce Board).

lar (transverse) direction.  $E_L$  is Young's modulus of elasticity for the longitudinal direction, and  $\mu_{LT}$  a material constant known as Poisson's ratio. Similarly, a transverse tensile stress  $\sigma_T$  causes a tensile strain  $\epsilon_T = \sigma_T/E_T$  in the transverse direction and a compressive strain  $\epsilon_L = -\mu_{TL}\epsilon_T$  in the longitudinal direction.  $E_T$  is Young's modulus of elasticity in the transverse direction, and  $\mu_{TL}$  a second Poisson's ratio.

When the material is isotropic,  $E_L = E_T$  and  $\mu_{LT} = \mu_{TL}$ , but these equalities do not hold for orthotropic materials. No shear strain  $\gamma_{LT}$  is set up when the normal stresses are applied in the principal directions, and shear stresses  $\tau_{LT}$  applied parallel to the grain and perpendicularly to it do not give rise to normal strains in the principal directions. The effect of a shear stress is just a change in angle; that is, a shear strain  $\gamma_{LT} = \tau_{LT}/G_{LT}$ , where  $G_{LT}$  is the modulus of elasticity in shear, or modulus of rigidity associated with the longitudinal and transverse directions. The deformations under the simultaneous action of normal and shearing stresses in the  $L$  and  $T$  directions can be summarized in the equations:

$$\epsilon_L = \sigma_L/E_L - \mu_{TL}\sigma_T/E_T \quad (1-1a)$$

$$\epsilon_T = \sigma_T/E_T - \mu_{LT}\sigma_L/E_L \quad (1-1b)$$

$$\gamma_{LT} = \tau_{LT}/G_{LT} \quad (1-1c)$$

Equations 1-1a-c are a generalization of Hooke's law for orthotropic plates.

Since the laws of elasticity are known only in directions  $L$  and  $T$ , and not in directions 1 and 2, the deformations caused by the stresses  $\sigma_1$ ,  $\sigma_2$ , and  $\tau_{12}$  cannot be determined directly. First the state of stress in the  $L$ ,  $T$  directions corresponding to the given stresses  $\sigma_1$ ,  $\sigma_2$ , and  $\tau_{12}$  must be found. Then the state of strain in the  $L$ ,  $T$  directions can be calculated from equations 1-1. Finally the state of strain in the 1,2 directions is determined from the calculated strains in the  $L$ ,  $T$  directions.

The calculations just outlined involve a transformation of stress and a transformation of strain. These purely geometric transformations can be carried out by means of a geometric construction involving the use of Mohr's circle.

#### TRANSFORMATION OF STRESS BY MOHR'S CIRCLE

The graphic construction used here was devised by O. C. Mohr<sup>1</sup> and is described in standard textbooks, as in Timoshenko's *Strength of Materials*.<sup>\*</sup> It was applied by Norris<sup>3</sup> to the solution of the stress-strain problems of wood and plywood. The technique adopted in this chapter is that suggested by Hoff.<sup>4</sup>

A horizontal base line  $BL$  and a vertical normal stress axis  $\sigma$ - $\sigma$  are drawn, as shown in Fig. 1-1B. Along the vertical axis are laid out distances proportional to the normal stresses, in the present case to  $\sigma_1 = 200$  psi upward, in the positive direction, from the base line, and  $\sigma_2 = -150$

<sup>\*</sup> Reference 2, part 1, page 38.



psi downward, that is, in the negative direction. The point on the  $\sigma$ - $\sigma$  axis corresponding to the horizontal normal stress is marked by the letter  $C$ . From point  $B$  corresponding to the vertical normal stress on the  $\sigma$ - $\sigma$  axis a line is drawn horizontally, that is, parallel to the shear stress indicated on the upper horizontal edge of the rectangle in Fig. 1-1A, and a distance proportional to twice the shear stress is measured in the direction of the shear stress, that is, to the right in the present example. Point  $B'$  so obtained as well as points  $B$  and  $C$  are on the stress circle whose center can be easily found as the point of intersection of the perpendicular bisectors of segments  $BB'$  and  $BC$ .

If the stress in any other direction is required, a parallel to the direction is drawn through point  $C$ . The normal stress in the new direction is proportional to the distance from the base line to the intersection of this parallel with the stress circle. Twice the shear stress corresponding to the new direction and to that perpendicular to it is proportional to the horizontal chord through the intersection point.

In the example of Fig. 1-1 the principal directions of elasticity subtend  $30^\circ$  and  $120^\circ$  with the vertical. The former is parallel to the fibers indicated in Fig. 1-1A and is denoted as the longitudinal ( $L$ ) direction, and the latter is perpendicular to the fibers and is designated as the transverse ( $T$ ) direction. A parallel to the fibers through  $C$  cuts the circle in point  $D'$ . Hence the normal stress along the fibers is represented by the segment  $OD$ . Similarly, the normal stress in the transverse direction is obtained by drawing a perpendicular to the fibers through  $C$ , projecting point  $E'$  upon the  $\sigma$ - $\sigma$  axis, and measuring the distance  $OE$ . The shear stress associated with the  $L, T$  directions is one half of the distance  $D'D''$  measured with the appropriate scale. It is negative, since the length of the chord representing twice the shear stress decreases from  $BB'$  to zero as line  $CB$  is rotated to the position  $CF'$ , changes sign, and increases again in absolute value as the line is rotated further from position  $CF'$  to position  $CD'$ .

#### CALCULATION OF THE STRAIN IN THE PRINCIPAL DIRECTIONS

The values scaled off from Fig. 1-1B are:

$$\sigma_L = 156 \text{ psi}$$

$$\sigma_T = -106 \text{ psi}$$

$$\tau_{LT} = -126.5 \text{ psi}$$

These values are indicated in Fig. 1-1C.

## Transformation of Strain by Mohr's Circle 11

The strains in the principal directions can be calculated from equations 1 if the elastic constants of the material are known. If the plate is a plank of flat-sawn spruce, the elastic constants are: \*

$$\begin{aligned} E_L &= 1,430,000 \text{ psi} \\ E_T &= 51,400 \text{ psi} \\ G_{LT} &= 52,800 \text{ psi} \\ \mu_{LT} &= 0.539 \\ \mu_{TL} &= 0.0194 \end{aligned} \tag{1-2}$$

Substitution of these values of the elastic constants and the values of the stresses just determined in equations 1 yields:

$$\begin{aligned} \epsilon_L &= 0.000149 \\ \epsilon_T &= -0.002119 \\ \gamma_{LT} &= -0.00240 \end{aligned}$$

### TRANSFORMATION OF STRAIN BY MOHR'S CIRCLE

The state of strain in the 1,2 directions can be obtained from that in the  $L,T$  directions by means of Mohr's circle. The strains are indicated in Fig. 1-1*D*, and the circle is constructed in Fig. 1-1*E*. First lines are drawn parallel to the known normal strains. Line  $\epsilon-\epsilon$  is parallel to the longitudinal strain  $\epsilon_L$  prevailing in the direction of the fibers, and the base line  $BL$  is parallel to the transverse strain  $\epsilon_T$  which exists perpendicularly to the fibers.  $\epsilon_L = 0.000149$  is laid out along the  $\epsilon-\epsilon$  axis upward (in the positive direction) from point  $O$ , the intersection of the  $\epsilon-\epsilon$  axis with the base line, and  $\epsilon_T = -0.002119$  is laid out downward (in the negative direction). The latter point is marked  $C$ . The shear strain  $\gamma_{LT} = -0.00240$  causes a leftward shift of the upper edge of the rectangle shown in Fig. 1-1*D*, and consequently  $\gamma_{LT}$  is laid out to the left from point  $B$ . The new point  $B'$  as well as points  $B$  and  $C$  lie on the strain circle whose center is easily found as the intersection of the perpendicular bisectors of segments  $BB'$  and  $BC$ .

The strain circle contains all the data related to the state of strain of the rectangle under the action of the stresses indicated in Fig. 1-1*A*. Of particular interest are the normal strains in directions 1 and 2. The

\* These data are taken from Table 2-3 and Table 2-5 of reference 5. In agreement with the procedure recommended, the value of the modulus in the table was increased by 10 per cent to correct for shear deflections.

former can be determined by passing a vertical (parallel to direction 1) through  $C$ . The distance of its intersection  $D'$  from the base line, that is, distance  $DO$ , is proportional to  $\epsilon_1$ . Similarly, the strain  $\epsilon_2$  in direction 2 is proportional to the distance  $EO$ . The shear strain  $\gamma_{12}$  associated with directions 1,2 is proportional to the chord  $D'D''$  through  $D'$  drawn parallel to the base line.

From Fig. 1-1E the following numerical values can be scaled off:

$$\epsilon_1 = 0.00062$$

$$\epsilon_2 = -0.00259$$

$$\gamma_{12} = 0.00075$$

The shear strain is positive since the negative value of  $-0.00240$  associated with the  $L,T$  directions decreases to zero as line  $CB$  is rotated into position  $CF'$  where the chord parallel to the base line has zero length. From position  $CF'$  on the length of the chord it increases positively as position  $CD'$  is approached.

The numerical values just given constitute the solution of the strain problem of the orthotropic plate under the action of the stresses indicated in Fig. 1-1A.

#### PARTICULAR STRESS CIRCLES

In Fig. 1-2A a particular type of stress circle is shown, namely, the one that corresponds to a small rectangular board loaded only by a tensile stress  $\sigma_1 = 100$  psi (Fig. 1-2B). This stress is laid out vertically upward from the base line, and the end point of the segment is marked  $B$ . No shear stress is acting along the horizontal edges of the rectangle so that points  $B'$  and  $B$  coincide. Since  $\sigma_2 = 0$ , point  $C$  lies on the base line. Consequently the center of the stress circle is the point of the  $\sigma$ - $\sigma$  axis lying midway between  $B$  and  $C$ .

The stresses corresponding to any arbitrary direction can be found as in the preceding example. For instance, the normal stress for  $\alpha = 45^\circ$  is obtained by drawing line  $CD'$  and scaling off  $CD$ . Twice the shearing stress  $\tau_{LT}$  is proportional to the horizontal chord through  $D'$  which, in this case, happens to be a diameter. The fact that  $\tau_{LT}$  is negative can be understood if a similar but slightly different state of stress is investigated.

In Fig. 1-2C the stress circle is presented for the loading indicated in Fig. 1-2D which comprises a small positive shear stress  $\tau_{12} = 10$  psi in addition to the tensile stress  $\sigma_1 = 100$  psi. The circle is constructed in accordance with the rules given earlier. The positive shear stress

corresponding to the vertical direction  $CB$  decreases to zero as line  $CB$  is rotated to position  $CF'$  and increases again but negatively as the line rotates further toward position  $CD'$ . When the initial shear stress corre-

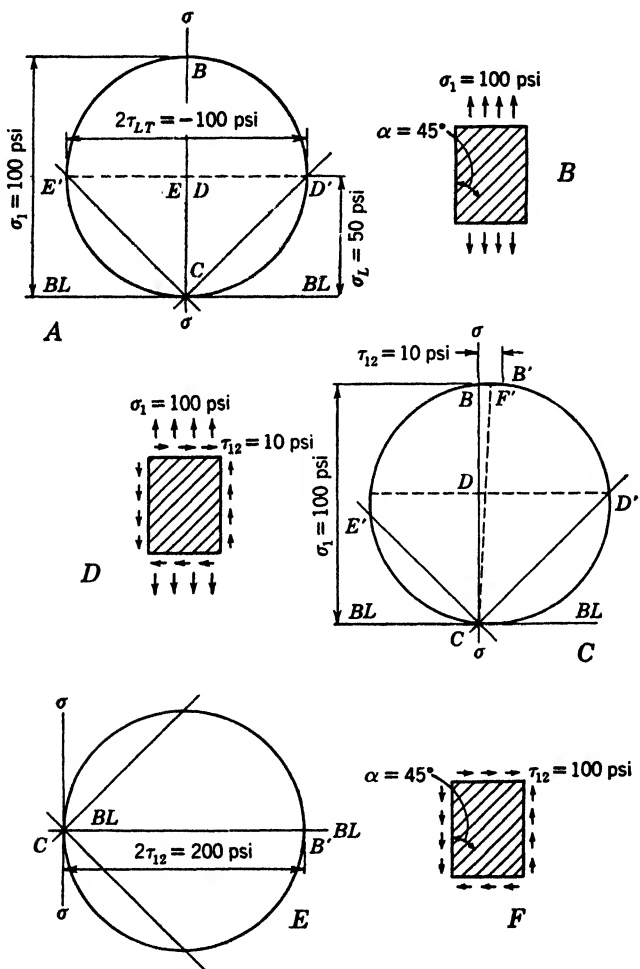


FIG. 1-2. Particular Stress Circles.

sponding to the horizontal direction is smaller, the change in sign from positive to negative occurs earlier. When the shear stress is zero for the 1,2 directions, the shear stress is negative for any direction of line  $CD'$  between the vertical and the horizontal swept during a clockwise rotation.

Figure 1-2*E* is a stress circle which represents the state of stress when there are neither vertical nor horizontal normal stresses, and the only loading of the small rectangle shown in Fig. 1-2*F* is the positive shear stress  $\tau_{12} = 100$  psi. The diagrams are self-explanatory, but it may be mentioned that in the case of a negative shear stress point *B'* would lie to the left of point *C*.

#### ACCURACY OF THE GRAPHIC CONSTRUCTION

The accuracy of the graphic construction depends on the scale of the drawings, the reliability of the instruments used, and the care exercised by the draftsman-computer. With average instruments, ordinary care, and diagrams drawn on 8½-by-11-in. sheets the error in the results is about 1 per cent of the maximum stress or strain represented.

#### ANALYTIC DETERMINATION OF THE ELASTIC PROPERTIES OF ORTHOTROPIC PLATES

The graphic construction presented in the preceding sections can be replaced by calculation. On page 9 analytic expressions have already been given for the stress-strain relations in the directions of the principal axes of elasticity. (In other directions the relationship is more involved since normal stresses give rise to shear strains as well as to normal strains and shear stresses cause normal strains as well as shear strains.) The additional equations needed in the calculations are those expressing the stresses in two mutually perpendicular directions in terms of the stresses in any other two mutually perpendicular directions. These equations are derived in textbooks<sup>6</sup> from the equilibrium of a prismatic element of a plate. With the sign convention of Fig. 1-3 the relationship between the stresses is:

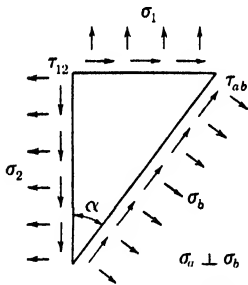


FIG. 1-3. Stresses Acting on a Prism.

$$\begin{aligned}\sigma_a &= \sigma_1 \cos^2 \alpha + \sigma_2 \sin^2 \alpha + \tau_{12} \sin 2\alpha \\ \sigma_b &= \sigma_1 \sin^2 \alpha + \sigma_2 \cos^2 \alpha - \tau_{12} \sin 2\alpha \\ \tau_{ab} &= \tau_{12} \cos 2\alpha + \left(\frac{1}{2}\right)(\sigma_2 - \sigma_1) \sin 2\alpha\end{aligned}\quad (1-3a)$$

Similar equations govern the transformation of strain:

$$\begin{aligned}\epsilon_a &= \epsilon_1 \cos^2 \alpha + \epsilon_2 \sin^2 \alpha + \left(\frac{1}{2}\right) \gamma_{12} \sin 2\alpha \\ \epsilon_b &= \epsilon_1 \sin^2 \alpha + \epsilon_2 \cos^2 \alpha - \left(\frac{1}{2}\right) \gamma_{12} \sin 2\alpha \\ \gamma_{ab} &= \gamma_{12} \cos 2\alpha + (\epsilon_2 - \epsilon_1) \sin 2\alpha\end{aligned}\quad (1-3b)$$

When the stresses are given in two mutually perpendicular directions 1,2 which do not coincide with the principal directions of elasticity  $L, T$ , the first step in the analytic procedure is the transformation of the stresses with the aid of equations 1-3a in order to obtain the stresses that prevail in the  $L, T$  directions. Equations 1-1 can then be used in the calculation of the strains in the principal directions. Finally the strains are transformed with the aid of equations 1-3b so that the strains prevailing in the original 1,2 directions may be determined.

The calculations indicated were carried out with algebraic symbols, and expressions were derived for the elastic properties of orthotropic plates loaded at arbitrary angles with the principal axes of elasticity. The equations obtained are presented in the following two articles.

#### ANALYTIC EXPRESSIONS IN THE CASE OF PURE TENSION

In Fig. 1-4A the direction of the grain, the  $L$  direction, is shown by the hatched lines in the rectangle.  $L$  and  $T$  are principal directions of elasticity. The loading consists of tensile stresses  $\sigma_1$  subtending an angle  $\alpha$  with the grain. The normal strain  $\epsilon_1$  in the direction of the stress can be calculated from the formula,

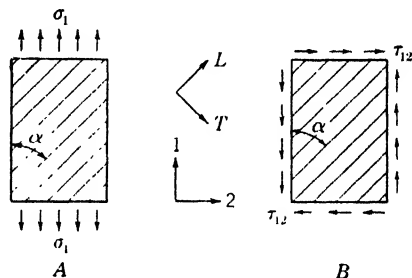


FIG. 1-4. Notation and Sign Convention for Analytic Expressions for Strain.

$$\epsilon_1 = \sigma_1 / E_1 \quad (1-4)$$

where the modulus of elasticity  $E$  in direction 1 can be obtained from the equation,

$$\frac{E_L}{E_1} = \cos^4 \alpha + \frac{E_L}{E_T} \sin^4 \alpha + \frac{1}{4} \left( \frac{E_L}{G_{LT}} - 2\mu_{LT} \right) \sin^2 2\alpha \quad (1-4a)$$

$E_L$  and  $E_T$  are Young's moduli of elasticity in the longitudinal (with-the-grain) and transverse (across-the-grain) directions,  $G_{LT}$  is the shear modulus corresponding to these principal directions, and  $\mu_{LT}$  is Poisson's ratio associated with a contraction in the transverse direction caused by a tensile stress in the longitudinal direction.

The transverse contraction in direction 2 is governed by the equation,

$$\epsilon_2 = -\mu_{12} \epsilon_1 \quad (1-5)$$

where Poisson's ratio  $\mu_{12}$  is given by the expression,

$$\mu_{12} = \frac{E_1}{E_L} \left\{ \mu_{LT} - \frac{1}{4} \left( 1 + 2\mu_{LT} + \frac{E_L}{E_T} - \frac{E_L}{G_{LT}} \right) \sin^2 2\alpha \right\} \quad (1-5a)$$

The shear strain  $\gamma_{12}$  caused in directions 1,2 by  $\sigma_1$  is

$$\gamma_{12} = -m_1 \sigma_1 / E_L \quad (1-6)$$

where the shear-extension constant  $m_1$  is

$$m_1 = \sin 2\alpha \left\{ \mu_{LT} + \frac{E_L}{E_T} - \frac{1}{2} \frac{E_L}{G_{LT}} - \cos^2 \alpha \left( 1 + 2\mu_{LT} + \frac{E_L}{E_T} - \frac{E_L}{G_{LT}} \right) \right\} \quad (1-6a)$$

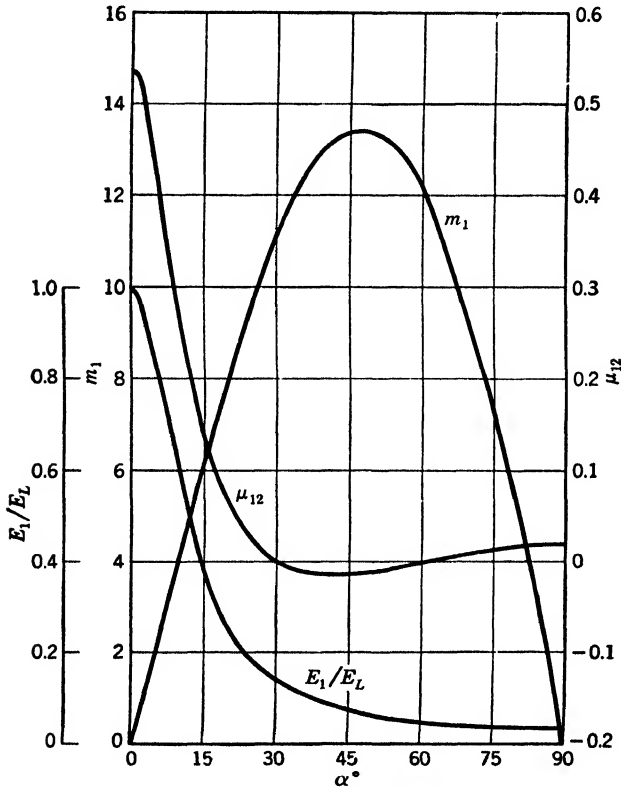


Fig. 1-5. Displacements Caused by Pure Tension in a Spruce Veneer.

(For notation see Fig. 1-4.) When  $\alpha$  is negative,  $E_1/E_L$  and  $\mu_{12}$  remain unchanged, and  $m_1$  becomes negative.

In Fig. 1-5 the elastic constants expressed in equations 1-4 to 1-6 are plotted for the case when the material is spruce having the properties stated on page 11. Other wood species exhibit a similar behavior, but the numerical values may differ considerably.

## ANALYTIC EXPRESSIONS IN THE CASE OF PURE SHEAR

When the loading consists only of shearing stresses  $\tau_{12}$  acting along edges situated relative to the principal directions  $L, T$  as shown in Fig. 1-4B, the shear strain  $\gamma_{12}$  can be calculated from the equation,

$$\gamma_{12} = \tau_{12}/G_{12} \quad (1-7)$$

where the modulus of shear  $G_{12}$  associated with directions 1,2 is defined by the equation,

$$\frac{G_{LT}}{G_{12}} = \frac{G_{LT}}{E_L} \left\{ \left( 1 + 2\mu_{LT} + \frac{E_L}{E_T} \right) - \left( 1 + 2\mu_{LT} + \frac{E_L}{E_T} - \frac{E_L}{G_{LT}} \right) \cos^2 2\alpha \right\} \quad (1-7a)$$

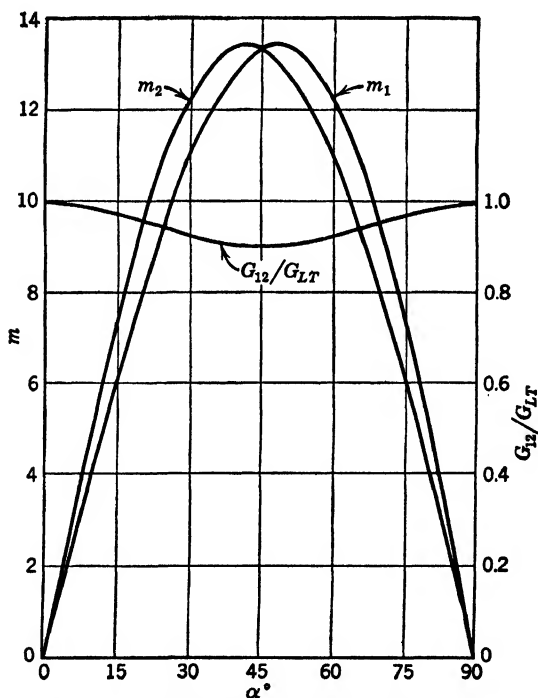


FIG. 1-6. Displacements Caused by Pure Shear in a Spruce Veneer.

(For notation see Fig. 1-4.) When  $\alpha$  is negative,  $G_{12}/G_{LT}$  remains unchanged and  $m_1$  and  $m_2$  change sign.

At the same time the applied shear stress causes a normal strain  $\epsilon_1$  in the 1 direction,

$$\epsilon_1 = -m_1\tau_{12}/E_L \quad (1-8)$$



where  $m_1$  is the shear-extension constant given in equation 1-6a, and a normal strain  $\epsilon_2$  in the 2 direction,

$$\epsilon_2 = -m_2\tau_{12}/E_L \quad (1-9)$$

where the second shear-extension constant  $m_2$  can be calculated from the equation,

$$m_2 = \sin 2\alpha \left\{ \mu_{LT} + \frac{E_L}{E_T} - \frac{1}{2} \frac{E_L}{G_{LT}} - \sin^2 \alpha \left( 1 + 2\mu_{LT} + \frac{E_L}{E_T} - \frac{E_L}{G_{LT}} \right) \right\} \quad (1-9a)$$

It may be noted that the multiplier of  $\tau_{12}$  in equation 1-8 is identical with the multiplier of  $\sigma_1$  in equation 1-6. This is in agreement with Maxwell's reciprocal theorem according to which the extension in the 1 direction caused by a unit shear stress acting along the 1,2 directions must be the same as the angular change in the 1,2 directions caused by a unit normal stress in the 1 direction.

In Fig. 1-6 the elastic constants expressed in equations 1-7 to 1-9 are plotted for the case when the material of the plate is spruce having the properties stated on page 11. Other wood species exhibit a similar behavior, but the numerical values may differ considerably.

#### CALCULATION OF THE EXAMPLE PRESENTED UNDER GENERALIZED HOOKE'S LAW (p. 7, Fig. 1-1)

The example stated on page 7 was solved with the aid of Mohr's circle. The graphic construction can be replaced by calculation if use is made of equations 1-4 to 1-9, or Figs. 1-5 and 1-6. The effects of the three stresses  $\sigma_1$ ,  $\sigma_2$ , and  $\tau_{12}$  are treated separately.

1. In direction 1, subtending an angle  $\alpha = 30^\circ$  with the grain,  $E_1/E_L = 0.134$  according to Fig. 1-5. Hence  $E_1 = 0.14 \times 1,430,000 = 200,000$  psi. With  $\sigma_1 = 200$  psi the strain becomes

$$\epsilon_1 = 200/200,000 = 0.001$$

In Fig. 1-5 at  $\alpha = 30^\circ$  the value of  $\mu_{12}$  is approximately zero, and that of  $m_1$  is 11. Consequently

$$\epsilon_2 = 0 \quad \gamma_{12} = -11 \times 200/1,430,000 = -0.00154$$

2. The stress  $\sigma_2 = -150$  psi subtends an angle  $\alpha = -60^\circ$  with the grain. The modulus of elasticity in this direction can be computed with the aid of the value  $E_1/E_L = 0.049$  taken from Fig. 1-5. However, in Fig. 1-1 the direction of the compressive stress of  $-150$  psi was denoted

as direction 2, so that the modulus in this direction must be designated as  $E_2$ . Hence,

$$E_2 = 0.049 \times 1,430,000 = 70,000 \text{ psi}$$

The compressive strain in direction 2 is, therefore,

$$\epsilon_2 = -150/70,000 = -0.00215$$

At  $\alpha = -60^\circ$ ,  $\mu_{12}$  is again zero while  $m_1 = -12.2$ . Consequently, the strain in direction 1,

$$\epsilon_1 = 0$$

The value of  $m_1$  is  $-12.2$ . On the other hand, along the vertical right-hand edge of the rectangular panel of Fig. 1-4 the positive sense of the shear stress associated with  $\sigma_1$  is upward, while that associated with  $\sigma_2$  is downward, so that the sign of  $m_1$  must be reversed. Substitution of  $+12.2$  in equation 1-6 yields

$$\gamma_{12} = -12.2 \times (-150)/1,430,000 = +0.00128$$

3. The shear stress  $\tau_{12}$  is equal to 50 psi. The constants needed in the calculations can be taken from the curves of Fig. 1-6. They are

$$G_{12}/G_{LT} = 0.92 \quad m_1 = 11 \quad m_2 = 12.2$$

Consequently,

$$\epsilon_1 = -11 \times 50/1,430,000 = -0.000384$$

$$\epsilon_2 = -12.2 \times 50/1,430,000 = -0.000426$$

$$\gamma_{12} = 50/(0.92 \times 52,800) = 0.00103$$

4. The total strain under the action of the total loading indicated in Fig. 1-1 is the sum of the strain quantities computed under paragraphs 1 to 3:

$$\epsilon_1 = 0.001 - 0.000384 = 0.000616$$

$$\epsilon_2 = -0.00215 - 0.000426 = -0.002576$$

$$\gamma_{12} = -0.00154 + 0.00128 + 0.00103 = +0.00077$$

It may be noted that the maximum deviation between the strain values obtained graphically and those computed with the aid of the diagrams is less than 1 per cent of the maximum strain.

#### CONNECTIONS BETWEEN THE ELASTIC CONSTANTS

As was stated on page 8, the normal strain in direction  $T$  caused by a normal stress  $\sigma_L$  in direction  $L$  is  $-\mu_{LT}\sigma_L/E_L$ , and the normal strain in direction  $L$  caused by a normal stress  $\sigma_T$  in direction  $T$  is

$-\mu_{TL}\sigma_T/E_T$ . In agreement with Maxwell's reciprocal theorem the two strains must be equal if the two stresses are of equal magnitude and sense. Consequently,

$$\mu_{LT}/\mu_{TL} = E_L/E_T \quad (1-10)$$

This equation is useful in the evaluation of tests carried out for determining the elastic constants. It can be stated in a more general form:

$$\mu_{pq}/\mu_{qp} = E_p/E_q \quad (1-10a)$$

where  $p$  and  $q$  refer to any two mutually perpendicular directions.

Another interesting connection between the elastic constants can be derived if  $\sigma_L = +1$  and  $\sigma_T = -1$  are assumed as the applied load, and the shear strain is calculated for edges subtending  $45^\circ$  with the principal directions. Since the  $45^\circ$  edges are under the action of pure shearing stresses of unit magnitude, the reciprocal of the shear strain calculated is the shear modulus,

$$G_{45^\circ} = \frac{E_L E_T}{E_L + E_T + 2E_T \mu_{LT}} \quad (1-11)$$

For isotropic materials  $E_L = E_T = E$ ,  $G_{45^\circ} = G$ , and  $\mu_{LT} = \mu$ , and equation 1-11 reduces to the known relation,

$$G = \frac{E}{2(1 + \mu)} \quad (1-11a)$$

#### EVALUATION OF STRAIN MEASUREMENTS

The state of strain and the state of stress in laminated plates are often investigated in experiments in which electric strain gages are cemented to the surface of the plate, and the strains are determined from the changes caused by them in the ohmic resistance of the electric gages. At any point on the surface of the plate the strains must be measured in three different directions in order to establish the state of strain completely. The strain in any other direction can then be obtained by the graphic construction whose principles were discussed on page 11.

As an example, let it be assumed that the parallel laminated Papreg plate of Fig. 1-7A is loaded in its plane and that the strains are measured on its surface in three directions designated as  $a$ ,  $b$ , and  $c$ . The directions are shown in Fig. 1-7B, and the strains are indicated. They are:

$$\epsilon_a = 6 \times 10^{-4} \quad \epsilon_b = 3 \times 10^{-4} \quad \epsilon_c = -3 \times 10^{-4}$$

The circle of strain is constructed in Fig. 1-7C. The direction of one of the strains, in the present example direction  $b$ , is chosen as the direction of the base line  $BL$ . The strains measured are laid off perpendicularly to  $BL$ . Point  $C$  is on the normal strain axis  $\epsilon-\epsilon$  at a distance  $\epsilon_b$  from the base line. Through point  $C$  are drawn straight lines parallel to  $a$  and  $c$ , and their intersections with parallels to the base line at dis-

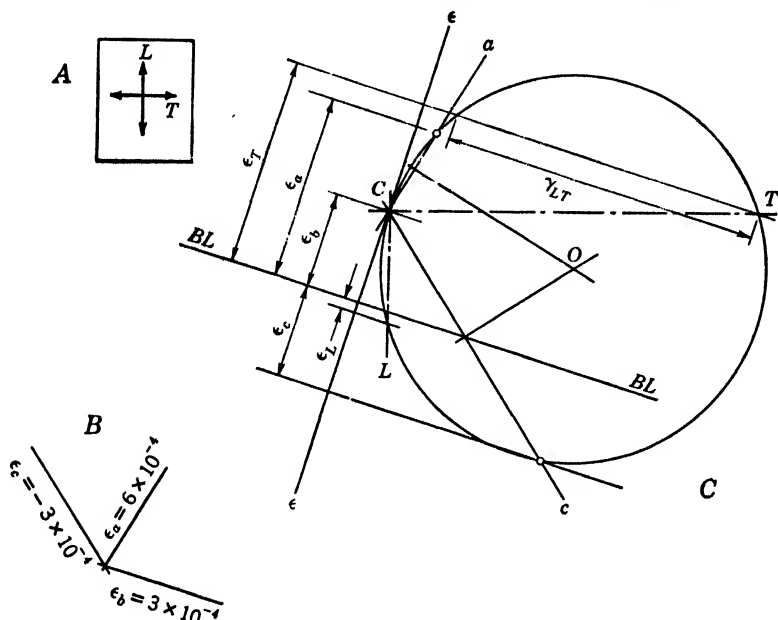


FIG. 1-7. Evaluation of Strain Gage Readings.

tances  $\epsilon_a$  and  $\epsilon_c$ , respectively, are marked by small circles. These two points as well as point  $C$  lie on the circle of strain. The center of the circle is found as the point of intersection of the perpendicular bisectors of the segments connecting the two points with  $C$ .

With the circle of strain drawn, the state of strain is known completely. Of particular interest are the strains in the principal directions of elasticity  $L$  and  $T$ . They are found by drawing parallels to  $L$  and  $T$  through point  $C$ . The distances from the base line of the points of intersection of these parallels with the circle are the normal strains sought. In the example,

$$\epsilon_L = -0.3 \times 10^{-4} \quad \epsilon_T = 6.5 \times 10^{-4}$$

The shear strain is the length of the chord, parallel to the base line, drawn through the intersection point. In the example,

$$\gamma_{LT} = 10.15 \times 10^{-4}$$

The normal stresses in the  $L$  and  $T$  directions can now be calculated since the connections between stress and strain are known in these directions. Solution of equations 1-1 for the stresses in the principal directions of elasticity yields

$$\begin{aligned}\sigma_L &= \frac{E_L}{1 - \mu_{LT}\mu_{TL}} (\epsilon_L + \mu_{TL}\epsilon_T) \\ \sigma_T &= \frac{E_T}{1 - \mu_{LT}\mu_{TL}} (\mu_{LT}\epsilon_L + \epsilon_T) \\ \tau_{LT} &= G_{LT}\gamma_{LT}\end{aligned}\tag{1-12}$$

The elastic constants of Papreg were determined by Erickson and Boller at the Forest Products Laboratory.<sup>7</sup> They found for parallel laminae:

$$\begin{aligned}E_L &= 3,200,000 \text{ psi} & E_T &= 1,600,000 \text{ psi} \\ G_{LT} &= 800,000 \text{ psi} & \mu_{LT} &= 0.4 \quad \mu_{TL} = 0.2\end{aligned}$$

The stresses in the principal directions are, therefore:

$$\begin{aligned}\sigma_L &= \frac{3,200,000}{1 - 0.4 \times 0.2} (-0.3 \times 10^{-4} + 0.2 \times 6.5 \times 10^{-4}) = 348 \text{ psi} \\ \sigma_T &= \frac{1,600,000}{1 - 0.4 \times 0.2} (-0.4 \times 0.3 \times 10^{-4} + 6.5 \times 10^{-4}) = 1110 \text{ psi} \\ \tau_{LT} &= 800,000 \times 10.15 \times 10^{-4} = 812 \text{ psi}\end{aligned}$$

The stresses in any other direction can be obtained by drawing the stress circles as shown on page 9. Further examples of stress and strain circles are given in Hoff's paper cited earlier<sup>4</sup> which also contains an extended bibliography. Among the articles listed Mindlin's<sup>8</sup> and Sibert's<sup>9</sup> may be mentioned as those presenting analytic expressions in convenient forms, and Osgood and Sturm's,<sup>10</sup> Osgood's,<sup>11</sup> Hill's,<sup>12</sup> and Williams'<sup>13</sup> as those developing graphic, or semigraphic constructions.

#### THE BEHAVIOR OF LAMINATED PLATES UNDER STRESSES ACTING IN THEIR PLANE

##### DERIVATION OF THE EQUATIONS FOR PURE TENSION OR COMPRESSION, AND FOR PURE SHEAR

When laminas are connected to form laminated plates, it is common practice to match them in order to obtain a balanced construction.

This means that, instead of gluing together, for instance, two veneers  $a$  and  $b$  of thickness  $t_a$  and  $t_b$ , respectively, a veneer of the type  $a$  of thickness  $t_a/2$  is cemented to each face of veneer  $b$  as shown in Fig. 1-8. Such a balanced laminate does not warp when the humidity of the air changes or when loads are applied in the plane of the laminate. It is permissible, therefore, to investigate the stresses and strains in this plane alone.

It was shown on page 15 that the application of a tensile stress to a lamina in the 1 direction causes normal strains in directions 1 and 2 and a change in the angle subtended by the edges, unless the lamina

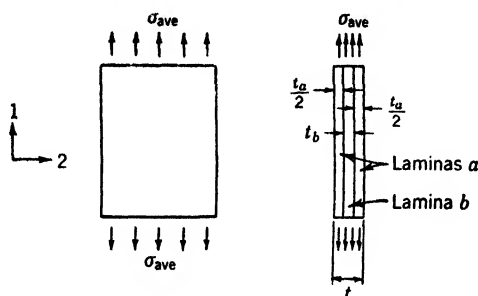


FIG. 1-8. Laminated Plate.

possesses elastic symmetry, and directions 1 and 2 are the principal axes of elastic symmetry. The applied tensile load can be distributed between the laminas in proportion to the tensile rigidity  $E_1 t$  of each so that the strain  $\epsilon_1$  is the same for each lamina. However, the transverse normal strain  $\epsilon_2$  and the shear strain  $\gamma_{12}$  would then, as a rule, be different in the two laminas. This cannot happen if the laminas are glued together. Consequently, in order to equalize the strain, normal stresses  $\sigma_2$  and shear stresses  $\tau_{12}$  must be set up between the laminas.

The strains in lamina  $a$  are, therefore:

$$\begin{aligned}\epsilon_{1a} &= \frac{\sigma_{1a}}{E_{1a}} - \mu_{21a} \frac{\sigma_{2a}}{E_{2a}} - m_{1a} \frac{\tau_{12a}}{E_{La}} \\ \epsilon_{2a} &= -\mu_{12a} \frac{\sigma_{1a}}{E_{1a}} + \frac{\sigma_{2a}}{E_{2a}} - m_{2a} \frac{\tau_{12a}}{E_{La}} \\ \gamma_{12a} &= -m_{1a} \frac{\sigma_{1a}}{E_{La}} - m_{2a} \frac{\sigma_{2a}}{E_{La}} + \frac{\tau_{12a}}{G_{12a}}\end{aligned}\quad (1-13)$$

If the subscript is changed from  $a$  to  $b$ , the equations represent the stress-strain relationships for lamina  $b$ .

Because of the type of loading assumed, the normal stresses  $\sigma_{1a}$  and  $\sigma_{1b}$  must be equivalent to the average normal stress  $\sigma$  applied, while the normal stresses  $\sigma_{2a}$  and  $\sigma_{2b}$  as well as the shear stresses  $\tau_{12a}$  and  $\tau_{12b}$  must be in equilibrium along the edges:

$$\begin{aligned}\sigma_{1a}t_a + \sigma_{1b}t_b &= \sigma t \\ \sigma_{2a}t_a + \sigma_{2b}t_b &= 0 \\ \tau_{12a}t_a + \tau_{12b}t_b &= 0\end{aligned}\tag{1-14}$$

The requirements of consistent deformations are:

$$\begin{aligned}\epsilon_{1a} &= \epsilon_{1b} = \epsilon_1 \\ \epsilon_{2a} &= \epsilon_{2b} = \epsilon_2 \\ \gamma_{12a} &= \gamma_{12b} = \gamma_{12}\end{aligned}\tag{1-14a}$$

Substitutions and algebraic manipulations yield the following three simultaneous equations:

$$\begin{aligned}A_{11}\sigma_{1a} + A_{12}\sigma_{2a} + A_{13}\tau_{12a} &= (\sigma/E_{1b})(t/t_at_b) \\ A_{21}\sigma_{1a} + A_{22}\sigma_{2a} + A_{23}\tau_{12a} &= -(\mu_{12b}\sigma/E_{1b})(t/t_at_b) \\ A_{31}\sigma_{1a} + A_{32}\sigma_{2a} + A_{33}\tau_{12a} &= -(m_{1b}\sigma/E_{Lb})(t/t_at_b)\end{aligned}\tag{1-15}$$

where

$$\begin{aligned}A_{11} &= \frac{1}{E_{1a}t_a} + \frac{1}{E_{1b}t_b} & A_{22} &= \frac{1}{E_{2a}t_a} + \frac{1}{E_{2b}t_b} & A_{33} &= \frac{1}{G_{12a}t_a} + \frac{1}{G_{12b}t_b} \\ A_{12} = A_{21} &= -\frac{\mu_{12a}}{E_{1a}t_a} - \frac{\mu_{12b}}{E_{1b}t_b} \\ A_{13} = A_{31} &= -\frac{m_{1a}}{E_{La}t_a} - \frac{m_{1b}}{E_{Lb}t_b} \\ A_{23} = A_{32} &= -\frac{m_{2a}}{E_{La}t_a} - \frac{m_{2b}}{E_{Lb}t_b}\end{aligned}\tag{1-15a}$$

If numerical values are substituted for the coefficients  $A$ , it is not difficult to solve equations 1-15 for the unknown stresses acting in lamina  $a$ . Solutions in a closed algebraic form are, however, cumbersome.

When the external load is a shear stress  $\tau_{12}$  distributed along the edges, a derivation similar to that previously given leads to the following equations:

$$\begin{aligned}
 A_{11}\sigma_{1a} + A_{12}\sigma_{2a} + A_{13}\tau_{12a} &= -(m_{1b}\tau_{12}/E_{Lb})(t/t_a t_b) \\
 A_{21}\sigma_{1a} + A_{22}\sigma_{2a} + A_{23}\tau_{12a} &= -(m_{2b}\tau_{12}/E_{Lb})(t/t_a t_b) \quad (1-16) \\
 A_{31}\sigma_{1a} + A_{32}\sigma_{2a} + A_{33}\tau_{12a} &= (\tau_{12}/G_{12b})(t/t_a t_b)
 \end{aligned}$$

The values of the constant coefficients  $A$  are those given in equation 1-15a.

### NUMERICAL EXAMPLE

The application of the theory to actual problems will now be shown in connection with the laminate sketched in Fig. 1-9. It consists of five layers  $a$  totaling  $t_a = 1/4$  in. having the grain subtend an angle

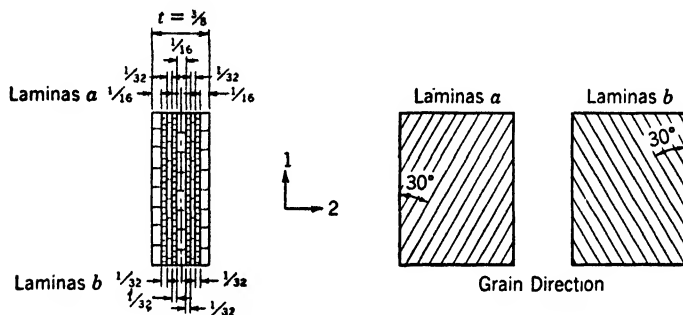


FIG. 1-9. Laminated Spruce Plate for Numerical Example.

$\alpha = 30^\circ$  with the vertical, and four layers  $b$  totaling  $t_b = 1/8$  in. having the grain subtend an angle  $\alpha = -30^\circ$  with the vertical. The loading consists of distributed vertical forces applied to the horizontal edges and having an average intensity of  $\sigma = 1000$  psi.

The material is spruce with the following moduli:

$$E_L = 1,430,000 \text{ psi} \quad E_T = 51,400 \text{ psi}$$

$$G_{LT} = 52,800 \text{ psi}$$

The variation of the elastic constants with the direction of the grain is plotted in Figs. 1-5 and 1-6. The values corresponding to lamina  $a$  with  $\alpha_a = 30^\circ$  are:

$$(E_1/E_L)_a = 0.14 \quad \mu_{12a} \cong -0.0001 \quad (G_{12}/G_{LT})_a = 0.926$$

$$m_{1a} = 10.98 \quad m_{2a} = 12.22$$

$E_2$  can be found by assuming lamina  $a$  in Fig. 1-8 to be rotated counter-clockwise through a right angle. The grain will then subtend an angle  $\alpha = -60^\circ$  with the vertical. From Fig. 1-5 the ratio,



$$E_1/E_L = 0.0486$$

when  $\alpha = 60^\circ$ , and the same value prevails for  $\alpha = -60^\circ$ . However, after the rotation the vertical direction is that denoted by 2, so that the subscript must be changed in the preceding equation,

$$(E_2/E_L)_a = 0.0486$$

The value of  $\mu_{21}$  can also be taken from Fig. 1-5 corresponding to  $\alpha = -60^\circ$ , but it is so small that it cannot be read accurately from the diagram. It can be calculated with the aid of equation 1-10,

$$\mu_{LT}/\mu_{TL} = E_L/E_T$$

with the present notation and values,

$$\mu_{21a} = \mu_{12a}(E_2/E_1)_a = -0.0001(0.0486/0.14) = -0.000035$$

For laminae  $b$  the angle  $\alpha_b = -30^\circ$ . The elastic constants can be found in the same manner as in the case of lamina  $a$ . They are

$$(E_1/E_L)_b = 0.14 \quad \mu_{12b} = -0.0001 \quad (G_{12}/G_{LT})_b = 0.926$$

$$\mu_{21b} = -0.000035 \quad m_{1b} = -10.98 \quad m_{2b} = -12.22$$

With  $t_a = 1/4$  in. and  $t_b = 1/8$  in. substitution of the preceding values in equations 1-15a yields

$$A_{11} = 6 \times 10^{-5} \quad A_{22} = 17.22 \times 10^{-5} \quad A_{33} = 24.6 \times 10^{-5}$$

$$A_{12} = 6 \times 10^{-9} \quad A_{13} = 3.07 \times 10^{-5} \quad A_{23} = 3.41 \times 10^{-5}$$

Hence equations 1-15 become

$$6 \times 10^{-5}\sigma_{1a} + 6 \times 10^{-9}\sigma_{2a} + 3.07 \times 10^{-5}\tau_{12a} = 6 \times 10^{-2}$$

$$6 \times 10^{-9}\sigma_{1a} + 17.22 \times 10^{-5}\sigma_{2a} + 3.41 \times 10^{-5}\tau_{12a} = 6 \times 10^{-6}$$

$$3.07 \times 10^{-5}\sigma_{1a} + 3.41 \times 10^{-5}\sigma_{2a} + 24.6 \times 10^{-5}\tau_{12a} = 9.23 \times 10^{-2}$$

These equations can be solved, for instance, by the method of determinants. The results are:

$$\sigma_{1a} = 858 \text{ psi} \quad \sigma_{2a} = -55 \text{ psi}$$

$$\tau_{12a} = 276 \text{ psi}$$

The stresses in laminae  $b$  can be calculated with the aid of equations 1-14:

$$\sigma_{1b} = 1,284 \text{ psi} \quad \sigma_{2b} = 110 \text{ psi}$$

$$\tau_{12b} = -552 \text{ psi}$$

Next the strains are calculated from equations 1-13:

$$\epsilon_1 = 2.17 \times 10^{-3} \quad \epsilon_2 = -3.14 \times 10^{-3} \quad \gamma_{12} = -0.50 \times 10^{-3}$$

A check on the accuracy of the calculations is available here since the strains must be the same whether computed for laminas *a* or laminas *b*. In the present example the variations were less than 1 per cent of the values.

The applied average stress of 1000 psi divided by the strain  $\epsilon_1$  yields the apparent modulus,

$$E_1 = 461,000 \text{ psi}$$

The strain  $\epsilon_2$  divided by the strain  $\epsilon_1$  and multiplied by  $-1$  is the apparent Poisson's ratio

$$\mu_{12} = 1.45$$

The numerical example illustrated that the state of stress and the state of strain in a laminated plate of this general nonsymmetric type are very complex. They cannot be calculated by short-cut methods. It is worth noting that in this example plates *b* carry 128 per cent of the average stress in the direction of the applied tension and are subjected in addition to shearing stresses amounting to 55 per cent of the applied average tensile stress.

#### FORMULAS FOR LAMINATED PLATES WITH ELASTIC SYMMETRY

When each of the laminas possesses elastic symmetry and the laminas are glued together so that their principal axes of elasticity are parallel, the resulting laminated plate also has elastic symmetry, and its principal axes are parallel to those of the individual laminas. In such a case it is advantageous to calculate the elastic properties of the laminated plate from those of the laminas in the directions of the principal axes. For these axes,

$$A_{13} = A_{31} = A_{23} = A_{32} = m_{1b} = m_{2b} = 0$$

Equations 1-15 reduce to

$$A_{11}\sigma_{1a} + A_{12}\sigma_{2a} = (\sigma/E_{1b})(t/t_at_b) \quad (1-17)$$

$$A_{21}\sigma_{1a} + A_{22}\sigma_{2a} = -(\mu_{12b}\sigma/E_{1b})(t/t_at_b)$$

The solution of equations 1-17 is

$$\begin{aligned} \sigma_{1a} &= \frac{\sigma}{E_{1b}} \frac{t}{t_at_b} \frac{A_{22} + \mu_{12b}A_{12}}{A_{11}A_{22} - A_{12}^2} \\ \sigma_{2a} &= -\frac{\sigma}{E_{1b}} \frac{t}{t_at_b} \frac{\mu_{12b}A_{11} + A_{12}}{A_{11}A_{22} - A_{12}^2} \end{aligned} \quad (1-18)$$

From equations 1-18 the strains can now be calculated with the aid of equations 1-1a and 1-1b. After algebraic transformations the following results are obtained:

$$\epsilon_{1a} = \frac{\sigma t}{E_{1a}t_a E_{1b}t_b} \frac{\left(\frac{1}{E_{2a}t_a} + \frac{1}{E_{2b}t_b}\right) - \left(\frac{\mu_{12a}^2}{E_{1a}t_a} + \frac{\mu_{12b}^2}{E_{1b}t_b}\right)}{\left(\frac{1}{E_{1a}t_a} + \frac{1}{E_{1b}t_b}\right)\left(\frac{1}{E_{2a}t_a} + \frac{1}{E_{2b}t_b}\right) - \left(\frac{\mu_{12a}}{E_{1a}t_a} + \frac{\mu_{12b}}{E_{1b}t_b}\right)^2} \quad (1-19)$$

$$\epsilon_{2a} = \frac{\sigma t}{E_{1a}t_a E_{1b}t_b} \frac{\mu_{12a}\mu_{12b}\left(\frac{\mu_{12a}}{E_{1a}t_a} + \frac{\mu_{12b}}{E_{1b}t_b}\right) - \frac{\mu_{12a}}{E_{2b}t_b} - \frac{\mu_{12b}}{E_{2a}t_a}}{\left(\frac{1}{E_{1a}t_a} + \frac{1}{E_{1b}t_b}\right)\left(\frac{1}{E_{2a}t_a} + \frac{1}{E_{2b}t_b}\right) - \left(\frac{\mu_{12a}}{E_{1a}t_a} + \frac{\mu_{12b}}{E_{1b}t_b}\right)^2}$$

The apparent modulus  $E_1$  in direction 1 follows now from the definition,

$$\sigma = E_1 \epsilon_1 = E_1 \epsilon_{1a}$$

Consequently,

$$E_1 = \sigma / \epsilon_{1a}$$

that is,

$$E_1 = \frac{E_{1a}t_a E_{1b}t_b}{t} \frac{\left(\frac{1}{E_{1a}t_a} + \frac{1}{E_{1b}t_b}\right)\left(\frac{1}{E_{2a}t_a} + \frac{1}{E_{2b}t_b}\right) - \left(\frac{\mu_{12a}}{E_{1a}t_a} + \frac{\mu_{12b}}{E_{1b}t_b}\right)^2}{\left(\frac{1}{E_{2a}t_a} + \frac{1}{E_{2b}t_b}\right) - \left(\frac{\mu_{12a}^2}{E_{1a}t_a} + \frac{\mu_{12b}^2}{E_{1b}t_b}\right)} \quad (1-20)$$

The apparent Poisson's ratio  $\mu_{12}$  follows from the defining equation,

$$\epsilon_{2a} = \epsilon_2 = -\mu_{12}\epsilon_1 = -\mu_{12}\epsilon_{1a}$$

Hence,

$$\mu_{12} = -\epsilon_{2a} / \epsilon_{1a}$$

Substitution yields

$$\mu_{12} = \frac{\frac{\mu_{12a}}{E_{2b}t_b} + \frac{\mu_{12b}}{E_{2a}t_a} - \mu_{12a}\mu_{12b}\left(\frac{\mu_{12a}}{E_{1a}t_a} + \frac{\mu_{12b}}{E_{1b}t_b}\right)}{\left(\frac{1}{E_{2a}t_a} + \frac{1}{E_{2b}t_b}\right) - \left(\frac{\mu_{12a}^2}{E_{1a}t_a} + \frac{\mu_{12b}^2}{E_{1b}t_b}\right)} \quad (1-21)$$

Values of  $E_2$  and  $\mu_{21}$  can be obtained from equations 1-20 and 1-21 upon interchanging the subscripts 1 and 2.

The expressions related to shearing also simplify in the case of an elastic symmetry. For the principal directions equations 1-16 are replaced by

$$A_{33}\tau_{12a} = (\tau_{12}/G_{12b})(t/t_a t_b) \quad (1-22)$$

After substitution of  $A_{33}$  from equations 1-15a, solution for  $\tau_{12a}$  yields

$$\tau_{12a} = \tau_{12} \frac{t}{t_a} \frac{G_{12a} t_a}{G_{12a} t_a + G_{12b} t_b} \quad (1-23)$$

Hence, the shear strain is

$$\gamma_{12} = \gamma_{12a} = \frac{\tau_{12} t}{G_{12a} t_a + G_{12b} t_b} \quad (1-24)$$

The effective shearing modulus  $G_{12} = \tau_{12}/\gamma_{12}$  becomes

$$G_{12} = (1/t)(G_{12a} t_a + G_{12b} t_b) \quad (1-25)$$

#### PLATES CROSS-LAMINATED OF A SINGLE MATERIAL

When the laminate is composed of layers of the same material with the grain alternately parallel and perpendicular to the grain of the reference layer, then the following equalities can be introduced into the equations:

$$E_{1b} = E_{2a} \quad E_{2b} = E_{1a} \quad \mu_{12b} = \mu_{21a} \quad \mu_{21b} = \mu_{12a}$$

Substitution in equation 1-20 and algebraic manipulations yield

$$E_1 = E_{1a} \frac{t_a}{t} \frac{\left(1 + k \frac{t_b}{t_a}\right) - \mu_{12a}^2 k^2 \frac{t^2}{t_a (k t_a + t_b)}}{1 - \mu_{12a}^2 k} \quad (1-26)$$

where  $k$  is the ratio of Young's modulus in direction 2 to that in direction 1 of the reference layer:

$$k = E_{2a}/E_{1a} \quad (1-26a)$$

Equation 1-21 reduces to

$$\mu_{12} = \mu_{12a} \frac{kt}{k t_a + t_b} \quad (1-27)$$

Equation 1-25 becomes

$$G_{12} = G_{12a} = G_{12b} \quad (1-28)$$

#### SIMPLIFIED FORMULAS FOR PLATES CROSS-LAMINATED OF A SINGLE MATERIAL WHEN $t_a = t_b$

When in a cross-laminated plate composed of layers of the same material the total thickness of the layers having the grain in direction 1

is the same as the total thickness of the layers having the grain in direction 2, the preceding formulas can be simplified considerably. The simplified formulas are:

$$E_1 = \frac{E_{1a} (1 + k)^2 - 4\mu_{12a}^2 k^2}{2 (1 + k)(1 - \mu_{12a}^2 k)} \quad (1-29)$$

$$\mu_{12} = \mu_{12a} \frac{2k}{k + 1} \quad (1-30)$$

The expression for the shearing rigidity remains as given in equation 1-28.

Equations 1-29 and 1-30 were used in computing values of  $E_1$  and  $\mu_{12}$  for a number of values of  $k$  and  $\mu_{12a}$ , and the results are plotted in

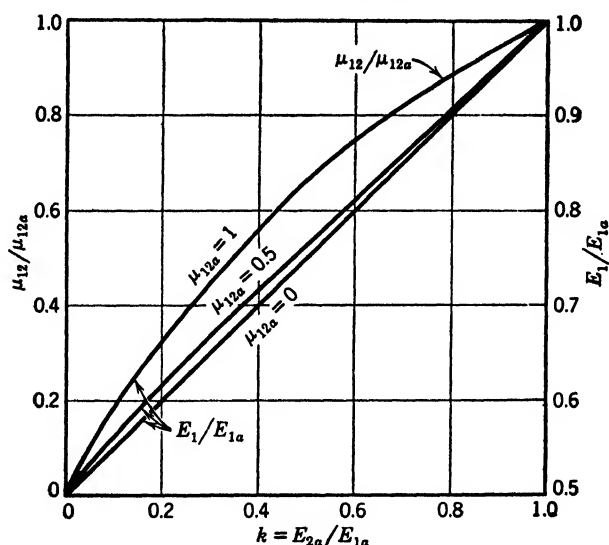


FIG. 1-10. Elastic Constants of Laminates.

Fig. 1-10. It may be seen that the assumption  $\mu_{12a} = 0$  is a good enough approximation in engineering calculations except when  $\mu_{12a}$  is close to unity.

#### PRACTICAL CALCULATION OF THE PROPERTIES OF CROSS-LAMINATED SPRUCE PLYWOOD

When the plate is cross-laminated of wood, it is customary to calculate its rigidity in tension or compression in one of the principal directions from the formula,

$$Et = \Sigma E_i t_i \quad (1-31)$$

where  $E$  is the apparent or average modulus in a principal direction,  $t$  the total thickness,  $E_i$  the modulus of the  $i$ th lamina in the same direction,  $t_i$  the thickness of the  $i$ th lamina, and the summation must be extended over all the laminas contained in the plywood.

An even more simplified calculation omits from the summation all those layers which have the grain perpendicular to the direction in which the apparent modulus is sought.

The results obtainable by the various methods are now compared by means of an example. It is assumed that the plywood is composed of the same layers as those shown in Fig. 1-9, but the fibers of the adjacent layers are arranged perpendicularly to one another.

Equation 1-31 yields

$$E_1 = \left(\frac{1}{3}\right)(2 \times 1,430,000 + 1 \times 51,400) = 970,500 \text{ psi}$$

$$E_2 = \left(\frac{1}{3}\right)(1 \times 1,430,000 + 2 \times 51,400) = 510,900 \text{ psi}$$

where 1 and 2 indicate the direction of the fibers in layers  $a$  and  $b$ , respectively.

If the transverse layers are neglected, the results are

$$E_1 = 953,300 \text{ psi}$$

$$E_2 = 476,700 \text{ psi}$$

The values obtained from equation 1-26 are

$$E_1 = 978,000 \text{ psi}$$

$$E_2 = 515,000 \text{ psi}$$

It can be concluded, therefore, that the differences between the results obtained by the exact formulas and those computed from the simple connection given in equation 1-31 are small enough to permit the use of equation 1-31 in practical calculations.

Poisson's ratio is in accordance with equation 1-27:

$$\mu_{12} = 0.539 \frac{0.036 \times 3}{0.036 \times 2 + 1} = 0.0543$$

Once the apparent moduli and Poisson's ratios of a laminated sheet are determined for the principal directions, they can be calculated for all the other directions according to the principles developed for the

orthotropic lamina on page 15. This was done for cross-laminated spruce plywood for the case when  $t_b = t_a$ .

From equation 1-29,

$$E_1 = E_2 = 747,000 \text{ psi}$$

From equation 1-30,

$$\mu_{12} = \mu_{21} = 0.0375$$

From equation 1-28,

$$G_{12} = G_{21} = 52,800 \text{ psi}$$

With these values the apparent elastic constants were determined from equations 1-4 to 1-9 for any angle  $\alpha$  subtended by the grain with

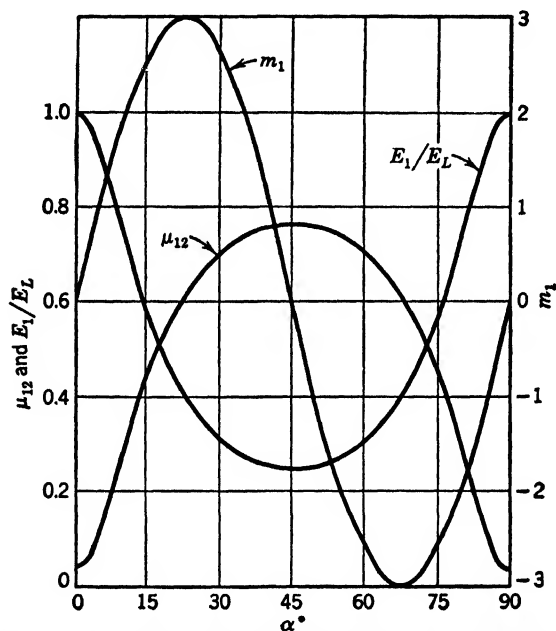


FIG. 1-11. Elastic Constants of Cross-Laminated Spruce.  $E_L = E_T = 747,000$  psi.

the principal directions. The results are plotted in Figs. 1-11 and 1-12. Comparison with Figs. 1-5 and 1-6 shows that cross lamination reduces materially the variation in the value of the apparent Young's modulus. For the single spruce veneer the maximum is 1,430,000 psi and the minimum 51,400 psi, while for the plywood the corresponding values are 747,000 psi and 186,000 psi. The shearing rigidity is increased by cross lamination for every angle  $\alpha$ , and the maximum value amounting to 6.76 times that found for the single veneer is reached when  $\alpha = 45^\circ$ .

## THE FAILURE OF LAMINATES UNDER STRESSES IN THEIR OWN PLANE

A laminate may fail through the failure of either one of its layers or the glue connecting the layers. In order to prevent the latter, it is advisable to secure the edges of laminated plates by reinforcements,

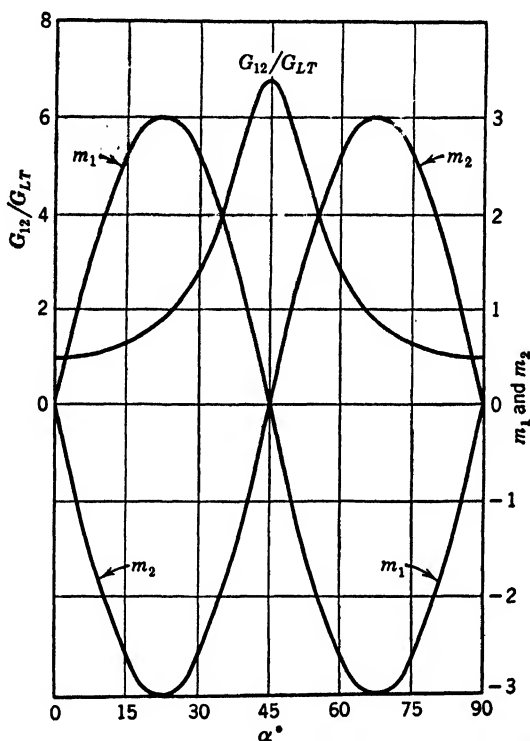


FIG. 1-12. Elastic Constants of Cross-Laminated Spruce.  $G_{LT} = 52,800$  psi.

rabbets, rivets, or the like, particularly when the loads are not applied parallel to the principal directions of elasticity of the plate. The numerical example discussed on page 25 shows that the application of normal stresses in a direction different from the principal directions may cause considerable shear stresses as well as normal stresses acting in a direction perpendicular to that of the stress applied. The shear stresses and the transverse normal stresses are transmitted from one layer to another along the edges of the plate and can attain values high enough to cause a separation of the layers if special precaution is not taken to prevent such an occurrence.



In the investigation of the failure of a layer of a laminate it must be kept in mind that the stresses in an individual layer may differ materially from the apparent stresses obtained by dividing the loads applied to the laminate by its cross-sectional area. As an example of the complexity of the states of stress and strain in the laminas under the action of simple tensile loads, the case discussed on page 25 may again be mentioned. When the failure of a laminate is to be predicted, the states of stress and strain in the individual laminas must, therefore, be first established. The connections between stress and strain in the different laminas developed in the preceding section and the stress and strain circles presented on page 8 are useful in determining the states of stress and strain in the laminas. It may be noted that, although this task is quite complex in the general case, it is reasonably simple when the loads are applied parallel to the principal directions of elasticity. With the stresses and strains calculated in a lamina, the imminence of failure can be judged on the basis of the theory of failure that applies best in the case of the material of the lamina.

When the lamina is of a ductile metal such as sheet steel or aluminum alloy, the maximum shear theory \* of failure may be used. The maximum shear stress in a lamina can be determined with the aid of the stress circle. If it is equal to one-half the yield stress of the material in simple tension, the lamina will yield. If it is smaller than that value, the lamina is safe. A more accurate theory of failure, developed by Huber and von Mises, is mentioned in Timoshenko's *Strength of Materials*. †

When the lamina is of wood, failure may occur by fracture across the fibers, fracture parallel to the fibers, or shearing between the fibers. It appears that the longitudinal normal stress at which the fibers will fracture is little influenced by the normal stress in the transverse direction or by the shear stress. The maximum stress theory ‡ should, therefore, apply. It predicts failure when the normal stress  $\sigma_L$  in the direction of the fibers reaches the value  $\sigma_{Lf}$ , which is the stress at failure in simple tension or compression. As an alternative, the maximum strain theory may be preferred, according to which failure occurs when the strain  $\epsilon_L$  in the direction of the fibers reaches the value  $\epsilon_{Lf} = \sigma_{Lf}/E_L$  obtained in simple tension or compression tests. There is not enough experimental evidence available to decide which of the two theories of failure is in better agreement with reality.

\* Reference 2, part 2, page 475.

† Reference 2, part 2, page 479.

‡ Reference 2, part 2, page 474.

Fracture parallel to the fibers, that is, splitting, is undoubtedly influenced by the shear stress, and shearing failure is certainly dependent on the normal stress perpendicular to the fibers. Sufficient experimental data, however, are not available for establishing accurately the connection between transverse normal stress and shear at failure. The following equation may be used and can be expected to give conservative results,

$$\frac{\sigma_T}{\sigma_{Tf}} + \frac{\tau_{LT}}{\tau_{LTf}} = 1 \quad (1-32a)$$

where  $\sigma_T$  is the transverse tensile normal stress,  $\sigma_{Tf}$  its value at failure in simple transverse tension,  $\tau_{LT}$  the shear stress, and  $\tau_{LTf}$  its value at failure in simple shear. Equation 32a indicates that transverse tension reduces the value of the shear stress at which sliding between the fibers begins, and the presence of a shear stress reduces the value of the transverse tension under which the wood splits. For instance, if  $\sigma_T$  is one quarter of  $\sigma_{Tf}$ , equation 1-32a becomes  $\tau_{LT}/\tau_{LTf} = 0.75$ , or, in other words, shear failure will occur when the shear stress is three quarters of the shear stress at which sliding begins in the absence of transverse tension.

Equation 1-32a may also be used, with some caution, when the transverse stress  $\sigma_T$  is compressive. The first term on the left-hand side of the equation is then negative, and thus the shearing stress at failure is greater than that causing failure in the absence of transverse compressive stresses. The equation is unlikely to be valid when the compressive stress is large.

It is very possible that the longitudinal stress also has an influence on shearing or splitting failure. This effect can be taken into account indirectly by replacing equation 1-32a by

$$\frac{\epsilon_T}{\epsilon_{Tf}} + \frac{\gamma_{LT}}{\gamma_{LTf}} = 1 \quad (1-33)$$

where  $\epsilon_T$  is the transverse shear strain,  $\epsilon_{Tf}$  its value at failure in the absence of shear strain,  $\gamma_{LT}$  the shear strain, and  $\gamma_{LTf}$  its value at failure in the absence of transverse normal strain.

ANC-18 suggests \* the use of the formula,

$$\left(\frac{\sigma_L}{\sigma_{Lf}}\right)^2 + \left(\frac{\sigma_T}{\sigma_{Tf}}\right)^2 + \left(\frac{\tau_{LT}}{\tau_{LTf}}\right)^2 = 1 \quad (1-32b)$$

\* Page 63 of reference 5.

where  $\sigma_L$ ,  $\sigma_T$ , and  $\tau_{LT}$  are the calculated longitudinal, transverse, and shear stress, respectively, in a lamina, and  $\sigma_{Lf}$ ,  $\sigma_{Tf}$ , and  $\tau_{LTf}$  are the values at failure of the longitudinal, transverse, and shear stress, respectively, in the absence of other stresses. More information on the failure of plywood is obtainable \* from ANC-18.

Extended experimental investigations will be required before it can be decided which one of the three equations, 1-32a, 1-33, or 1-32b, agrees best with reality.

No formulas have been developed for predicting the failure of plastic bonded textiles or Papreg under combined stress. Equation 1-32b or a more conservative one obtainable from it by substitution of the first power for the second in all the terms may be used until more information becomes available. Formulas similar to equations 1-32a and 1-33 might also be established.

## THE BENDING OF LAMINATED STRUCTURAL ELEMENTS

### THE BENDING OF BEAMS

As it was found on page 30 that the contraction of a lamina perpendicularly to the direction of an applied tension has little effect on the elastic properties of a cross laminate loaded in the plane of the laminate in the direction of one of the principal axes of elasticity, this effect will not be considered in the investigation of the more complex problem of the bending of a laminated beam. Assuming that the principal axes of elasticity of the laminas are oriented as the  $x$ ,  $y$ , and  $z$  axes in Fig. 1-13, and neglecting the contraction, one may express the bending rigidity  $EI$  of the beam by the formula,

$$EI = \sum E_i I_i \quad (1-34)$$

where  $E_i$  is the modulus of the  $i$ th lamina, and  $I_i$  the moment of inertia of its cross section with reference to the  $x$  axis which passes through the centroid of the weighted cross section. In the calculation of the centroid, the cross-sectional area of each lamina must be weighted by multiplying it by Young's modulus of the lamina. When the laminas are arranged symmetrically so that the beam is of a balanced construction, the axis of symmetry is, of course, the centroidal axis.<sup>14</sup>

In some problems it is advantageous to define an effective modulus in bending by solving equation 1-34 for  $E$ :

\* Pages 59-64 of reference 5.

$$\begin{aligned}
 E &= (1/I) \sum E_i I_i \\
 &= (12/wh^3) \sum E_i I_i
 \end{aligned}
 \tag{1-34a}$$

Equation 1-34 can be used for developing an expression for the bending rigidity of a beam of symmetric construction composed of two kinds of layers as shown in Fig. 1-13. The first kind has a thickness  $t_1$  and a modulus  $E_1$ . One of the layers of the first kind is located in the middle of the cross section so that its horizontal axis of symmetry coincides with the  $x$  axis. The second kind has a thickness  $t_2$  and a modulus  $E_2$ . The layers are counted from the  $x$  axis upward but the layer at the  $x$  axis is not counted, so that in Fig. 1-13 there are two layers of the

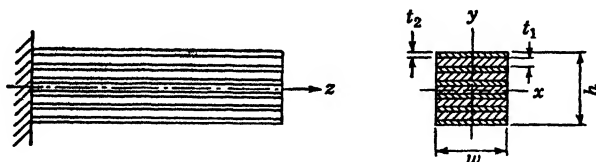


FIG. 1-13. Laminated Beam.

first kind ( $n_1 = 2$ ) and three layers of the second kind ( $n_2 = 3$ ). The bending rigidity of such a beam is

$$\begin{aligned}
 EI &= (w/12) \{ (2n_1 + 1)t_1^3 E_1 + 2n_2 t_2^3 E_2 + (t_1 + t_2)^2 [4n_1(n_1 + 1) \\
 &\quad \times (2n_1 + 1)t_1 E_1 + (2n_2 - 1)(2n_2)(2n_2 + 1)t_2 E_2] \}
 \end{aligned}
 \tag{1-35}$$

Cases of particular interest to which equation 1-35 can be applied are those in which the layers are of equal thickness:

When there are altogether three layers,  $n_1 = 0$  and  $n_2 = 1$ . Consequently,

$$EI = (wt^3/12)[E_1 + 26E_2]
 \tag{1-36a}$$

When there are altogether five layers,  $n_1 = 1$  and  $n_2 = 1$ . Hence,

$$EI = (wt^3/12)[99E_1 + 26E_2]
 \tag{1-36b}$$

When there are altogether seven layers,  $n_1 = 1$  and  $n_2 = 2$ . Then,

$$EI = (wt^3/12)[99E_1 + 244E_2]
 \tag{1-36c}$$

When there are altogether nine layers,  $n_1 = 2$  and  $n_2 = 2$ . Therefore,

$$EI = (wt^3/12)[485E_1 + 244E_2]
 \tag{1-36d}$$

The normal stress  $\sigma$  at any point in the cross section can be calculated from the equation,

$$\sigma = ME_y y / EI \quad (1-37)$$

where  $M$  is the bending moment at the section,  $E_y$  the modulus of the material at the point,  $y$  the distance of the point from the neutral axis, and  $EI$  the bending rigidity of the beam as calculated from the formulas quoted. It may be mentioned that the maximum normal stress in a laminate does not necessarily occur in the fibers farthest from the neutral axis. Not  $y$ , but  $E_y y$  must be a maximum in equation 1-37 for the normal stress to be a maximum, and this may be true in a lamina closer to the neutral axis if its modulus is larger than that of the extreme lamina.

Along any horizontal line distant  $y$  from the  $x$  axis in the section of the laminated beam shown in Fig. 1-13 the shear stress is

$$\tau = VQ^* / EIw \quad (1-38)$$

where  $V$  is the shear force,  $Q^*$  the weighted static moment, with respect to the  $x$  axis, of the portion of the cross section lying above the horizontal line,  $EI$  the bending rigidity of the laminate as given in equations 1-34 to 1-36, and  $w$  the width of the cross section. In the calculation of  $Q^*$  each lamina must be weighted by multiplying its cross-sectional area by the modulus of the lamina. The maximum shear stress always occurs at the neutral axis since  $Q$  has its maximum value there.

As an example, the shear stress is now calculated in the glue joint between the second and the third laminas from the top in the laminated beam of Fig. 1-13. The weighted static moment of the top lamina is  $wt_2 E_2 (2.5 t_1 + 2.5 t_2)$ , and that of the second lamina  $wt_1 E_1 (2t_1 + 2t_2)$ . The sum is, therefore,

$$Q^* = w(t_1 + t_2)(2t_1 E_1 + 2.5t_2 E_2) \quad (a)$$

The bending rigidity of the beam can be calculated from equation 1-35. Substitution in equation 1-38 of this value as well as of the value of the shear force and that of  $Q^*$  as given in equation  $a$  yields the shear stress in the glue joint.

An expression can be derived easily for the maximum value of the weighted static moment of the laminated beam of balanced construction shown in Fig. 1-13. This is needed in the calculation of the maximum shear stress from the formula,

$$\tau_{max} = VQ^*_{max} / EIw \quad (1-38a)$$

The expression for  $Q^*_{max}$  is

$$Q^*_{max} = (w/8) \{ t_1 E_1 [t_1 + 4n_1(n_1 + 1)(t_1 + t_2)] + 4n_2^2 t_2 (t_1 + t_2) E_2 \} \quad (1-39)$$

where  $t_1$  and  $E_1$  are the thickness and the modulus, respectively, of the layers of the first kind, and  $t_2$  and  $E_2$  the corresponding values for the layers of the second kind. The designation first is applied to that kind of layer to which the layer at the neutral axis belongs.  $n_1$  is the number of layers of the first kind above the neutral axis, not counting the one situated at the neutral axis, and  $n_2$  is the number of layers of the second kind above the neutral axis.

When the thickness of all the layers is the same,

$$t_1 = t_2 = t$$

equation (1-39) reduces to

$$Q^*_{max} = (wt^2/8)\{[1 + 8n_1(n_1 + 1)]E_1 + 8n_2^2E_2\} \quad (1-40)$$

Formulas are given now for particular cases.

When there are altogether three layers,  $n_1 = 0$  and  $n_2 = 1$ . Consequently,

$$Q^*_{max} = (wt^2/8)[E_1 + 8E_2] \quad (1-40a)$$

When there are altogether five layers,  $n_1 = 1$  and  $n_2 = 1$ . Then,

$$Q^*_{max} = (wt^2/8)[17E_1 + 8E_2] \quad (1-40b)$$

When there are altogether seven layers,  $n_1 = 1$  and  $n_2 = 2$ . Hence,

$$Q^*_{max} = (wt^2/8)[17E_1 + 32E_2] \quad (1-40c)$$

When there are altogether nine layers,  $n_1 = 2$  and  $n_2 = 2$ . Therefore,

$$Q^*_{max} = (wt^2/8)[49E_1 + 32E_2] \quad (1-40d)$$

It may be mentioned that although the maximum shear stress always occurs at the neutral axis, the danger of failure by shearing may be greater in another lamina if its load-carrying capacity in shear is smaller than that of the lamina at the neutral axis.

The deflection of a laminated beam can be calculated from the formulas developed in *Strength of Materials*, provided the value of the bending rigidity substituted in the formulas is that given in equations 1-34 to 1-36. When the material has a small shearing rigidity, the deflection due to shear should be added to the deflection due to the bending moment. The calculation of the shear deformations can be carried out by an approximate method as described, for instance, by Timoshenko.† When the shear modulus varies materially in the laminas, an average value can be calculated from the shear strain energy stored in the beam.‡

† Reference 2, part 1, page 170.

‡ Reference 2, part 1, page 298.

A more detailed investigation of the deflections is needed in the case of sandwich-type beams, the core of which has very little resistance to shear. This problem is treated on page 60. The deflections of plywood beams were calculated by March.<sup>15</sup>

### THE BENDING OF PLATES

A plate was defined in the introduction (page 6) as a body, one dimension of which, namely, the thickness, is much smaller than its other two dimensions. Figure 1-14 pictures a plate. The  $x$  and  $y$  axes

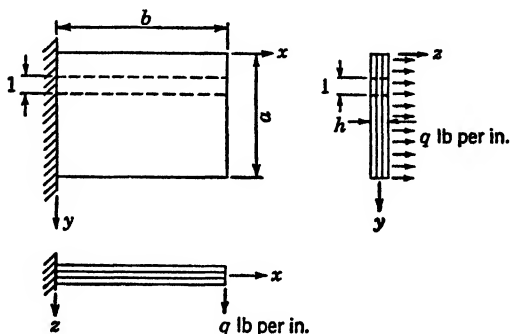


FIG. 1-14. Laminated Plate.

are laid out in the median plane of the plate, and the thickness of the plate is measured in the direction of the  $z$  axis.

If the plate is rigidly clamped along the  $y$  axis and a distributed load  $q$ , measured in pounds per inch, is applied along the free side parallel to the  $y$  axis, the plate will deflect very much like a beam, and the rules of calculation stated on page 36 may be used. The only difference between the behavior of beams of conventional section and the plate is that the latter is slightly stiffer. The increased stiffness can be accounted for by the use of  $E'_x$  in the calculations in place of the modulus  $E_x$ :

$$E'_x = E_x / (1 - \mu_{xy}\mu_{yz}) \quad (1-41)$$

The greater stiffness can be explained by comparing the plate of Fig. 1-14 with the beam of unit width cut from it as indicated by the dotted lines. The downward load  $q$  at the right end of the cantilever beam causes tensile stresses in the upper fibers and compressive stresses in the lower fibers in the  $x$  direction. Consequently, in the transverse ( $y$ ) direction, the beam will shrink on the upper and expand on the lower surface, and the transverse strain will be equal to the longitudinal ( $x$ )

strain multiplied by Poisson's ratio  $\mu_{xy}$ . In the plate transverse strains cannot occur, because the 1-in.-wide strip indicated by the dotted lines is bordered on both sides by other strips, equally loaded, which have a tendency to distort in exactly the same manner. Hence, transverse stresses are induced of a sufficient magnitude to keep the original width of the beam cut from the plate unchanged. If the stress in the  $x$  direction on the top surface of the beam is denoted as  $\sigma_x$ , the transverse stress is  $\sigma_y = \frac{E_y}{E_x} \mu_{xy} \sigma_x$ . In turn, this stress now causes a shortening of the top fibers in the  $x$  direction amounting to  $\mu_{yx} \sigma_y / E_y = \mu_{xy} \mu_{yx} \sigma_x / E_x$  per inch width. The original elongation of the top fibers per inch length,

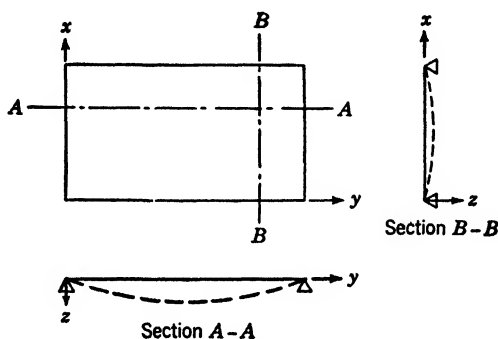


FIG. 1-15. Simply Supported Plate.

$\sigma_x / E_x$ , is therefore reduced by the amount  $\mu_{xy} \mu_{yx} \sigma_x / E_x$  so that the apparent modulus of elasticity  $E'$  of the plate is as given in equation 1-41. A deviation from the state of stress and strain described is noticeable only near the edges  $b$ , but the effect of the edges is not important.\*

An entirely different situation arises when edges of the plate parallel to both the  $x$  and the  $y$  axes are supported. Such problems cannot be solved with the aid of the beam theory, and recourse must be had to the more complex plate theory.<sup>17</sup> When, for instance, the plate of Fig. 1-15 is loaded by a uniformly distributed load and all the four edges are supported by knife edges, the deflected shape of the plate will be as shown by the dotted lines. The four edges remain straight, and the original median plane of the plate distorts to a doubly curved surface.

The behavior of an orthotropic plate under transverse loads can be defined by a partial differential equation and by the appropriate bound-

\* Reference 16 and reference 2, part 2, page 120.



ary conditions. When the  $x$  and  $y$  directions are principal directions of elasticity, the equation is \*

$$D_x \frac{\partial^4 w}{\partial x^4} + 2D_{xy} \frac{\partial^4 w}{\partial x^2 \partial y^2} + D_y \frac{\partial^4 w}{\partial y^4} = q \quad (1-42)$$

where  $w$  is the deflection of a point of the median plane in the  $z$  direction,  $q$  is the intensity of the distributed load in pounds per square inch, and the rigidity of the plate is characterized by the following quantities:

$$D_x = \frac{E_x h^3}{12(1 - \mu_{xy}\mu_{yx})} \quad (1-43a)$$

which is the bending rigidity of a strip in the  $x$  direction having unit width;

$$D_y = \frac{E_y h^3}{12(1 - \mu_{xy}\mu_{yx})} \quad (1-43b)$$

which is the bending rigidity of a strip in the  $y$  direction having unit width; and

$$D_{xy} = \frac{\mu_{xy} E_y h^3}{12(1 - \mu_{xy}\mu_{yx})} + \frac{G h^3}{6} = \frac{\mu_{yx} E_x h^3}{12(1 - \mu_{xy}\mu_{yx})} + \frac{G h^3}{6} \quad (1-43c)$$

which is a quantity connected with the resistance to twisting of a strip of unit width.

In equations 1-43 the moduli  $E_x$  and  $E_y$  are average moduli in bending as defined in equation 1-34a,  $G$  is the average shear modulus, and  $h$  the total thickness of the plate.

The differential equation was derived independently by F. Gehring (1860), M. J. Boussinesq (1879), and M. T. Huber (1914).† In his book Huber gives the solution of the differential equation for many cases of loading and various boundary conditions. The solutions were first obtained for a plate having a width  $b$  and an infinite length. The loads were represented by suitable Fourier expansions and the deflections calculated by integration of the differential equation. The solutions of the problems of the finite rectangular plate were derived from those related to the infinite plate by means of mirrored images of the loads and the use of the principle of superposition.

When the load is distributed uniformly along a single line as shown in

\* Page 188 of reference 17.

† Historic remarks, together with a complete development of the theory, may be found in reference 18. See also reference 19 and page 188 of reference 17.

Fig. 1-16, the maximum deflection  $d$  of a very long plate is, according to Huber,

$$d = 0.01015 \frac{qb^3}{D_y} \left[ \frac{1}{2} \frac{D_{xy}}{D_y} + \frac{1}{2} \sqrt{\frac{D_x}{D_y}} \right]^{-1/2} \quad (1-44)$$

provided

$$D_x D_y \neq D_{xy}^2 \quad (1-44a)$$

and

$$d = 0.01015 \frac{qb^3}{D_y} \sqrt[4]{\frac{D_y}{D_x}} \quad (1-45)$$

when

$$D_x D_y = D_{xy}^2 \quad (1-45a)$$

In the case of a load  $W$  concentrated in the middle of a very long plate, the maximum deflection is

$$d = 0.01696 \frac{Wb^2}{D_y} \left[ \frac{1}{2} \frac{D_{xy}}{D_y} + \frac{1}{2} \sqrt{\frac{D_x}{D_y}} \right]^{-1/2} \quad (1-46)$$

provided

$$D_x D_y \neq D_{xy}^2 \quad (1-46a)$$

and

$$d = 0.01696 \frac{Wb^2}{D_y} \sqrt[4]{\frac{D_y}{D_x}} \quad (1-47)$$

when

$$D_x D_y = D_{xy}^2 \quad (1-47a)$$

A plate can be considered as very long with an accuracy sufficient for practical calculations if its length  $a$  satisfies the following inequality,

$$a \geq 3b \sqrt[4]{(D_x/D_y)} \quad (1-48)$$

This inequality is applicable when

$$D_x D_y = D_{xy}^2 \quad (1-48a)$$

but it can also be used with satisfactory results when equation 1-48a is only approximately satisfied. Huber's book also contains similar criteria for the cases in which equation 1-48a does not hold.

It is noted that in the case of a plate of finite length the use of a formula derived for a very long plate always yields exaggerated values for the deflections and consequently leads to conservative design.

The maximum bending moments occur in the middle of the plate. In the case of a load  $qb$  distributed uniformly along a line, as shown in Fig. 1-16, they are:

$$M^*_x = 0.0929 \, qb \left[ \sqrt{\frac{D_x}{D_y}} + \mu_{yx} \frac{D_x}{D_y} \right] \left[ \frac{1}{2} \frac{D_{xy}}{D_y} + \frac{1}{2} \sqrt{\frac{D_x}{D_y}} \right]^{-1/2} \quad (1-49)$$

$$M^*_y = 0.0929 \, qb \left[ \mu_{xy} \sqrt{\frac{D_y}{D_x}} + 1 \right] \left[ \frac{1}{2} \frac{D_{xy}}{D_y} + \frac{1}{2} \sqrt{\frac{D_x}{D_y}} \right]^{-1/2}$$

where  $M^*_x$  is the bending moment in the  $x$  direction per inch width of the plate, and  $M^*_y$  the bending moment in the  $y$  direction per inch length of the plate.

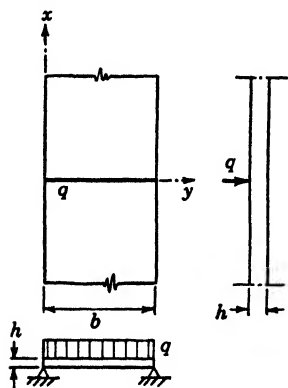


FIG. 1-16. Very Long Simply Supported Plate Subjected to Load  $W = qb$  Distributed Uniformly along a Line.

When the load  $qb$  is not distributed over the entire width  $b$  of the plate but only over a portion  $c$  of the width, the maximum bending moments can still be calculated from equations 1-49 provided a different numerical factor is used. The factor 0.0929 must be replaced by 0.2736 when  $c/b = \frac{1}{2}$ , and by 0.3370 when  $c/b = \frac{1}{4}$ . It is assumed that the loaded portion  $c$  of the width  $b$  is situated symmetrically with respect to the vertical axis of symmetry of the plate as shown in Fig. 1-17.

As  $c$  decreases, the numerical factor increases and approaches infinity as  $c$  approaches zero while the product  $q^*c = qb$  remains constant. The fact that the theory yields infinite bending moments for a concentrated load has no physical significance since in reality no finite load can be applied to an infinitely small area. However, the theory indicates that it is advisable to distribute loads to a reasonably large area.

It may be mentioned that in the case of a finite plate the use of a formula derived for an infinitely long plate always yields exaggerated values for moments as well as for deflections and consequently leads to conservative design.

Many problems of the bending of orthotropic plates were solved by H. W. March<sup>20</sup> who was interested in obtaining useful expressions for designers of plywood structures. In his investigations March used both rigorous methods of solving the differential equation and an approximate

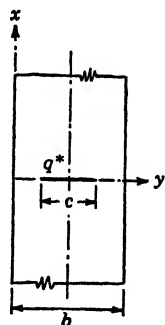


FIG. 1-17. Very Long Simply Supported Plate Subjected to Load  $W = q^*c = qb$ .

strain energy approach based on an assumed deflected shape. His results will be given for the case of a load uniformly distributed over the entire surface of the plate.

If a plate of width  $b$  in the  $y$  direction and an infinite length in the  $x$  direction is subjected to a uniform load  $q$ , the deflections of the plate are independent of the value of the co-ordinate  $x$ , since the edges of the plate parallel to the  $y$  axis cannot have any effect. The maximum deflection is constant all along the axis of symmetry of the plate parallel to the  $x$  axis. It has the same value as the deflection of a beam of length  $b$  and unit width subjected to a uniform load  $q$  except for the effect of the restraint to expansion in the  $x$  direction which was discussed at the beginning of this article. When the edges of the plate parallel to  $x$  are simply supported, the maximum deflection is

$$d_{ss.0} = \frac{5(1 - \mu_{xy}\mu_{yx})}{32} \frac{qb^4}{E_y h^3} \quad (1-50a)$$

and, when these edges are clamped,

$$d_{cl.0} = \frac{1 - \mu_{xy}\mu_{yx}}{32} \frac{qb^4}{E_y h^3} \quad (1-50b)$$

When the length of the plate in the  $x$  direction is finite and is denoted by  $a$ , the deflections vary in the  $x$  direction with the maximum deflection occurring in the middle of the plate. This maximum can be computed from the formula,

$$d_{ss} = k_{ss} d_{ss.0} \quad (1-51)$$

when all the edges are simply supported, and, from the formula,

$$d_{cl} = k_{cl} d_{cl.0} \quad (1-52)$$

when all the edges are clamped. The coefficients  $k_{ss}$  and  $k_{cl}$  are plotted against the parameter  $(a/b) \sqrt{E_y/E_x}$  in Fig. 1-18. The curves are reproduced from Forest Products Laboratory Mimeo. 1312. They were obtained by integration of the differential equation of the orthotropic plate under the condition  $D_x D_y > D_{xy}^2$  which holds true in the case of plywood plates, substitution of the values of the mechanical properties that prevail in plywood plates, and averaging out the numerical values obtained. It might be mentioned that the variation from the average curve was found very slight in the case of the types of plywood investigated.

March reports experiments carried out at the Forest Products Laboratory with 17 plates freely supported and 16 plates clamped along the

edges. In the former case, the measured maximum deflection was on the average 20 per cent smaller than the calculated value, and the greatest deviation amounted to 32 per cent. In the latter case, the observed maximum deflection was on the average 40 per cent larger

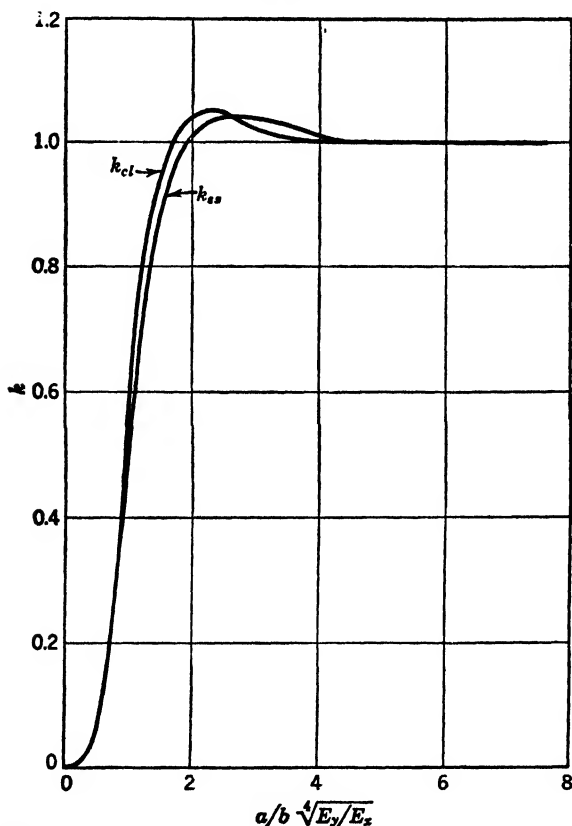


FIG. 1-18. Multiplying Factors for the Calculation of the Deflections of Rectangular Plates.

than the calculated value, and the greatest deviation was 83 per cent. It was believed that the deviations were mainly due to the boundary conditions in the experiments. It was found difficult to approach the condition of a perfect absence of either the moment or the end rotation.

Forest Products Laboratory Mimeo. 1312 also contains expressions for the calculation of the bending moments which, however, are not quite so simple as the formulas quoted. When the length of the plate is reasonably large, March suggests that beam formulas be used.

All the equations presented in this article are valid only when the deflections are small, as a rule not greater than the thickness  $h$  of the plate. When the deflections increase beyond this limit, the median plane of the plate stretches and helps to carry the loads. In such a case the classical bending theory must be replaced by a theory of large deflections. Solutions of this problem were also given by March.<sup>20</sup>

## THE BUCKLING OF LAMINATED STRUCTURAL ELEMENTS

### THE BUCKLING OF COLUMNS

Figure 1-19 shows a laminated column, supported on knife edges, compressed in a testing machine. The load  $P$  is applied along the axis of the column which is assumed to be perfectly straight. It has been known since the investigations of Euler, Engesser, and von Kármán<sup>21-24</sup> that under such conditions a perfect column remains straight until a critical value  $P_{cr}$  of the load is reached. When the critical value is exceeded by the slightest amount, the column becomes unstable and buckles as shown in Fig. 1-19B. If the load is not applied perfectly centrally or if the column has a slight initial curvature, the column will become more and more curved as the loading progresses. The deviations from the original straight line or slightly curved shape increase slowly in the initial stages of loading and more and more rapidly as the critical load is approached. In every case the curvature will increase sufficiently below the critical value of the load to cause the column to break or to yield and distort permanently. Consequently the critical load represents the maximum possible load-carrying capacity of the column. The straighter the column is originally and the better it is centered under the load, the closer this maximum can be approached.

If the compressive stress in every lamina is less than the proportional limit of the material when the column is under the action of  $P_{cr}$ , the following formula can be used for the calculation of the critical load:

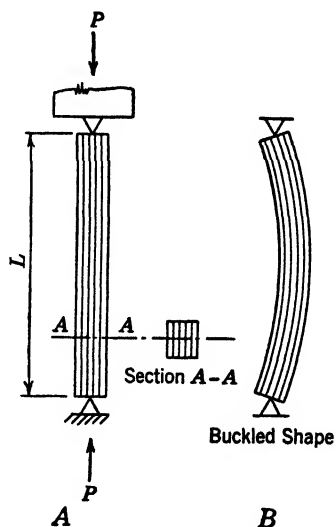


FIG. 1-19. Laminated Column.

$$- \frac{\pi^2 EI}{L'^2} \quad (1-53)$$

where  $EI$  is the bending rigidity of the column as computed from equation 1-34, and  $L'$  the so-called reduced length of the column which is equal to the distance between two consecutive inflection points of the deflected shape of the axis of the column. Figure 1-20 illustrates that  $L' = L$  when the ends of the column are simply supported,  $L' = L/2$  when they are rigidly clamped, and  $L' = 2L$  when one end is clamped and the other free.

If the proportional limit is exceeded in a lamina when the column is under the action of the critical load  $P_{cr}$ , Young's modulus ceases to

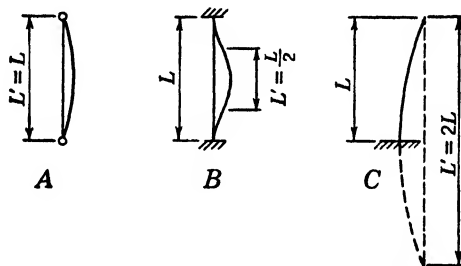


FIG. 1-20. Effective Length of a Column.

be the factor of proportionality between stress and strain for that lamina. When the column buckles, the various laminas are stretched or compressed, in addition to being bent, depending on their location in the laminate. The increases in the compressive stress are proportional to the instantaneous value of the modulus, the so-called tangent modulus  $E_t$ , while the decrements are proportional to the original modulus  $E$  because only the elastic portion of the deformations can be recovered. Consequently, the resistance of each lamina to bending at the moment of buckling is proportional to some average modulus, the value of which lies between  $E$  and  $E_t$  and depends on the location of the lamina. The buckling load can then be calculated from the formula,

$$P_{cr} = \frac{\pi^2 (EI)_{red}}{L'^2} \quad (1-54)$$

where  $(EI)_{red}$  is the reduced bending rigidity which can be obtained from equation 1-34 if in the summation  $E_i$  is replaced by the appropriate value  $E_{i, red}$  of the reduced modulus for each lamina. The values of  $E_{i, red}$  can be determined on the basis of considerations as presented, for

instance, by Timoshenko,<sup>†</sup> but the algebraic transformations become quite lengthy when there are many layers of different materials.

When the shearing rigidity of the laminate is small, the buckling load is reduced below the value predicted by equations 1-53 or 1-54. In such a case, part of the lateral deflections shown in Fig. 1-19*B* is caused by bending and the rest by shear. The buckling load  $P_S$  can be calculated from the Engesser formula,<sup>‡</sup>

$$P_S = \frac{P_{cr}GA^*}{P_{cr} + GA^*} \quad (1-55)$$

where  $P_{cr}$  is the buckling load as computed from equation 1-53 or equation 1-54 without consideration of the shear deformations,  $G$  the average shear modulus, and  $A^*$  the effective area in shear. The latter differs from the actual cross-sectional area  $A$ , since the shear stress is not distributed uniformly over the cross section. In the case of a rectangle  $A^* = (\frac{5}{6})A$ .

When the column is long and its shearing rigidity  $GA^*$  large as compared to  $P_{cr}$ , the denominator in equation 1-55 is approximately equal to  $GA^*$  so that  $P_S$  is approximately equal to  $P_{cr}$ . When the shearing rigidity of the central layers of the laminate is considerably smaller than that of the external layers, as is generally true for sandwich construction, the buckling load should be calculated as suggested on page 75.

## THE BUCKLING OF PLATES

When a plate is placed in a testing machine and compressed, it buckles very much like a beam as shown in Fig. 1-21*A*. The buckling load may be calculated from the equations on pages 48 and 49, but the modulus should be multiplied by the factor  $1/(1 - \mu_{xy}\mu_{yx})$ , as suggested on page 40, since the strain in the transverse direction must be zero because of the plate action.

An entirely different problem arises when not only the two opposite loaded edges of the plate are supported. Then the buckled shape is not cylindrical but has double curvature. In Fig. 1-21*B* and *C* the two unloaded edges are in V grooves and, consequently, must remain straight when the compressive load is applied. The two loaded edges remain straight because of the friction between plate and testing machine. In the case illustrated, the buckled shape comprises two bulges which may be seen from the horizontal sections drawn in Fig. 1-21*D* and the vertical section *D-D* indicated in Fig. 1-21*B*.

<sup>†</sup> Page 156 of reference 24.

<sup>‡</sup> Reference 25 and page 139 of reference 24.





the edges  $b$ ,  $N_y$  the tensile force per inch parallel to the  $y$  axis applied along the edges  $a$ , and  $N_{xy}$  is the shear force per inch applied along edges  $a$  and  $b$ .  $N_x$  and  $N_y$  are negative when they represent compression. The rigidities  $D_x$ ,  $D_{xy}$ , and  $D_y$  were defined in equations 1-43.

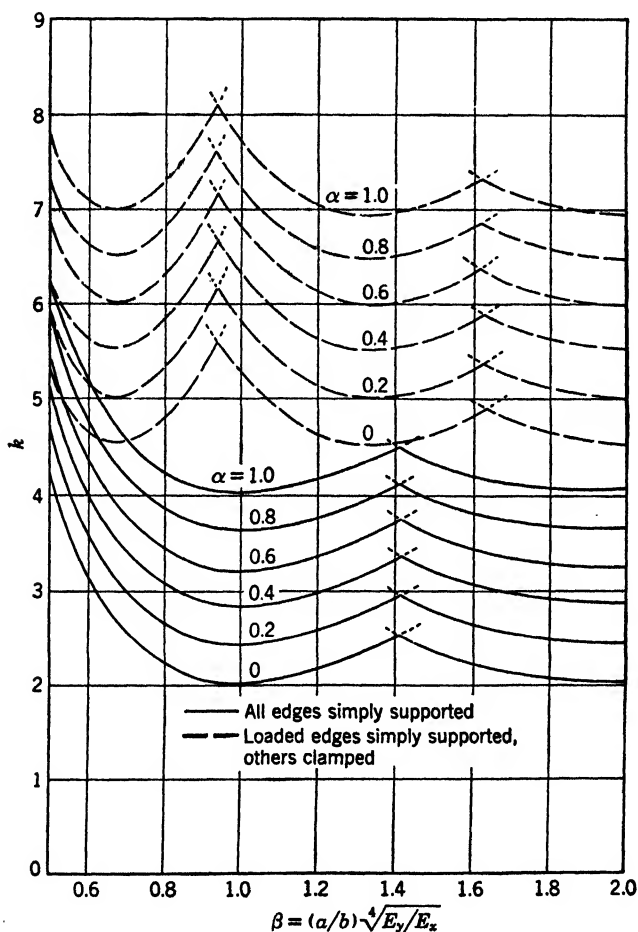


FIG. 1-22. Coefficients of Plate Buckling in Compression.

Equation 1-56 has been solved for a few combinations of loading and boundary conditions. Timoshenko\* gives the solution for the case when  $N_x = -\sigma_{cr}h$ ,  $N_{xy} = N_y = 0$ , and the edges are simply supported. R. C. T. Smith<sup>28</sup> calculated the critical stress of plates compressed in a

\* Page 381 of reference 24.

principal direction of elasticity for three different sets of boundary conditions:

Case 1. Loaded edges clamped, unloaded edges simply supported.

Case 2. Loaded edges simply supported, unloaded edges clamped.

Case 3. All edges rigidly clamped.

Timoshenko found an exact solution of his problem, and so did Smith in cases 1 and 2. Case 3 was solved by Smith by means of the strain energy method.

The results of all these calculations can be presented in the form,

$$\sigma_{cr} = k \frac{\pi^2 \sqrt{E_x E_y}}{12(1 - \mu_{xy}\mu_{yx})} \left(\frac{h}{b}\right)^2 \quad (1-57)$$

where  $E_x$  is the effective modulus in bending of strips parallel to the applied load, which can be calculated from equation 1-34a,  $E_y$  the same quantity for strips running in the transverse direction,  $\mu_{xy}$  and  $\mu_{yx}$  are Poisson's ratios as defined on page 8,  $h$  is the thickness of the plate,  $b$  the length of the loaded edge, and  $k$  a constant plotted in Figs. 1-22 and 1-23. The figures are reproduced from a publication by Dale and Smith.<sup>27</sup> The factor  $k$  is plotted against the quantity,

$$\beta = (a/b) \sqrt[4]{(E_y/E_x)} \quad (1-58)$$

where  $a$  is the length of the unloaded edge and  $b$  that of the loaded edge of the plate. A family of curves is presented for each set of edge conditions, and the parameter  $\alpha$  of the family is

$$\alpha = \frac{\mu_{xy}E_y + 2(1 - \mu_{xy}\mu_{yx})G}{\sqrt{E_x E_y}} \quad (1-59)$$

For an isotropic material  $\alpha = 1$ , and for three-ply used in aircraft  $\alpha = 0.5$  in good approximation.

If the quantities involved in the problem just discussed are expressed by the coefficients of differential equation 1-56, the following expressions are obtained:

$$\sigma_{cr} = k \frac{\pi^2 \sqrt{D_x D_y}}{hb^2} \quad (1-57a)$$

$$\beta = (a/b) \sqrt[4]{(D_y/D_x)} \quad (1-58a)$$

$$\alpha = \frac{D_{xy}}{\sqrt{D_x D_y}} \quad (1-59a)$$

Equations 1-57a, 1-58a, and 1-59a are preferable to equations 1-57, 1-58, and 1-59 when the rigidities of the plate defined in equations 1-43 are determined experimentally.

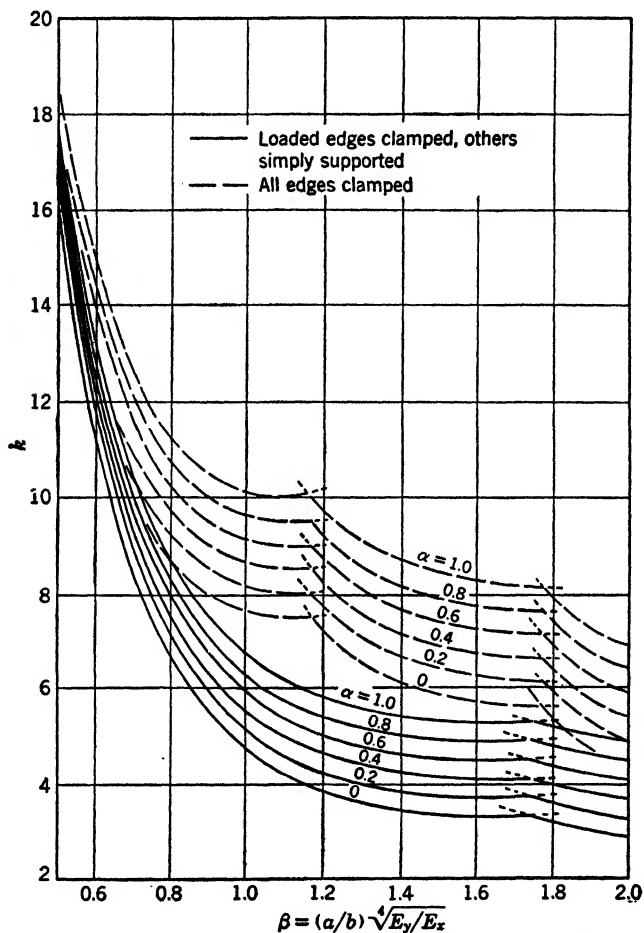


FIG. 1-23. Coefficients of Plate Buckling in Compression.

The buckling of orthotropic plates under shear loads was investigated by Bergmann and Reissner.<sup>28</sup> Differential equation 1-56 was integrated under the following conditions:  $N_x$  and  $N_y$  are equal to zero,  $D_x$  is small or zero, and the plate is infinitely long in the  $x$  direction. At Reissner's suggestion, this work was continued by Seydel<sup>29-31</sup> who found approximate solutions for both infinite and finite rectangular plates for the case

when  $D_x$ ,  $D_y$ , and  $D_{xy}$  all have arbitrary values. The results of these investigations related to infinite plates were presented by Bergmann and Reissner in an appendix to the second part of their publication in the following form:

$$\tau_{cr} = \frac{\sqrt{2D_y D_{xy}}}{(b/2)^2 h} \left[ 8.3 + 1.525 \left( \frac{D_x D_y}{D_{xy}^2} \right) - 0.493 \left( \frac{D_x D_y}{D_{xy}^2} \right)^2 \right] \quad (1-60)$$

when

$$D_x D_y < D_{xy}^2 \quad (1-60a)$$

and

$$\tau_{cr} = \frac{\sqrt[4]{D_x D_y^3}}{(b/2)^2 h} \left[ 8.125 + 5.64 \sqrt{\frac{D_{xy}^2}{D_x D_y}} - 0.6 \frac{D_{xy}^2}{D_x D_y} \right] \quad (1-61)$$

when

$$D_x D_y > D_{xy}^2 \quad (1-61a)$$

The formulas suggested for finite rectangular plates by Seydel \* are

$$\tau_{cr} = C \frac{\sqrt[4]{D_x D_y^3}}{(b/2)^2 h} \quad (1-62)$$

provided the plate parameter  $\theta$  is not smaller than unity

$$\theta = \frac{\sqrt{D_x D_y}}{D_{xy}} \geq 1 \quad (1-62a)$$

The value of the numerical factor  $C$  must be taken from Fig. 1-24. Only the curves corresponding to  $\theta = 1$ , 2, and infinity, as well as the points on the  $C$  axis for  $\theta = 1.41$ , 3, 5, and 10 were given by Seydel. The curves corresponding to the latter four values of  $\theta$  were drawn in by eyesight in agreement with Seydel's proposal.

In Fig. 1-24  $C$  is plotted against the effective side ratio  $\beta$  defined as

$$\beta = \frac{b}{a} \sqrt[4]{\frac{D_x}{D_y}} \quad (1-62b)$$

When  $\beta$  is found to be greater than unity,  $a$  and  $b$  as well as the subscripts  $x$  and  $y$  should be interchanged in equations 1-62, 1-62a, and 1-62b, in order to permit the use of the graph of Fig. 1-24.

Tests carried out with panels of corrugated sheet at the Deutsche Versuchsanstalt für Luftfahrt gave results in satisfactory agreement with Bergmann and Reissner's and Seydel's theories. Numerical values

\* The formulas as well as the graph are taken from reference 31.

were not calculated by Seydel for the case when  $\theta < 1$ , but suggestions were given in his last-mentioned paper regarding such calculations.

An extended theoretical and experimental investigation was carried on at the Forest Products Laboratory in order to establish the buckling stresses in compression, shear, or combinations of compression and shear of flat rectangular plywood panels under various edge conditions. The results of the theoretical work, carried on by the energy method,

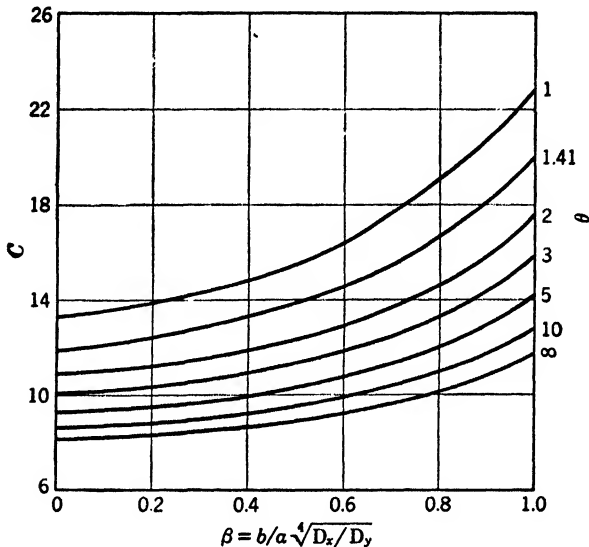


FIG. 1-24. Coefficients of Plate Buckling in Shear.

as well as comparisons of theory and experiment were published in a series of reports.<sup>32-38</sup> Many graphs from these reports are reproduced<sup>5</sup> in ANC-18.

A theoretical investigation was carried out by Goland and Aleck<sup>39, 40</sup> in order to determine the orientation of the grain in plywood that gives the highest buckling load. It was found that the best results are obtained when the grain of adjacent plies is perpendicular. Other angles between the grain of alternate plies, notably also  $0^\circ$  corresponding to parallel laminates, give smaller buckling loads under compressive or shear loads as well as under combinations of shear and compression or tension. For optimum results the grain of the face plies should subtend an angle of about  $40^\circ$  with the direction of the applied compressive load and about  $60^\circ$  with that of the applied shear load. In the case of shear care should be exercised in determining the correct sign of the

angle as shown in Fig. 1-25, since the buckling load at  $-60^\circ$  is much smaller.

Goland and Aleck's theory was developed in general terms for very long plates but some of the conclusions were drawn from an evaluation of the theory for mahogany plywood having five layers of equal thickness. Such panels were tested at the Curtiss-Wright Research Laboratories and confirmed some of the results predicted. A maximum of the compressive buckling stress curve was observed at about  $40^\circ$ , but the

value was slightly smaller than the buckling stress corresponding to  $0^\circ$  and  $90^\circ$  face grain directions.

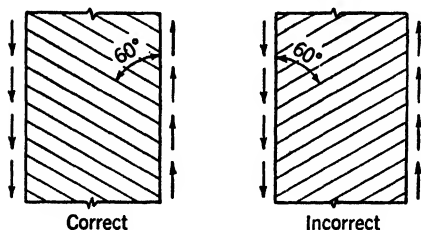


FIG. 1-25. Best Arrangement of Face Grain for High Buckling Load in Shear.

#### THE BUCKLING OF SHELLS

The calculation of the buckling stress of an orthotropic shell is somewhat unreliable because of the scarcity of experimental data and because in the case of iso-

tropic shells, where experimental data are available, theory and experiment are not in good agreement. This latter statement is correct as long as a linear theory is used in the calculations. Von Kármán, Tsien, and Dunn<sup>41-43</sup> showed that a nonlinear theory is capable of predicting the buckling stress of an isotropic shell with sufficient accuracy.

A linear theory of buckling of orthotropic shells was developed by Flügge<sup>44</sup> who stated the buckling condition as the requirement that a determinant vanish. This criterion was not given in a form suitable for practical computations. The condition was simplified and worked out in detail by Dschou<sup>45</sup> for the case of an axially and circumferentially reinforced thin-walled monocoque cylinder loaded axially in uniform compression. Dschou's results are useful in the case of thin-walled reinforced aluminum-alloy airplane structures, but they do not apply equally well to nonreinforced orthotropic shells. Furthermore, even in reinforced thin-walled construction empirical factors are needed in order to bring the theory in agreement with experiment.

Similarly, a linear theory of the buckling of orthotropic curved shells subjected to uniform axial compression developed by Taylor<sup>46</sup> was found to predict far too high critical stresses when it was compared to experiments carried out at the California Institute of Technology<sup>47</sup> on thin-walled reinforced aluminum-alloy monocoque cylinders.

Recently an analysis of the buckling of long thin-walled plywood cylinders was carried out by March<sup>48,49</sup> along lines similar to those suggested by von Kármán and Tsien. It was observed at the Forest Products Laboratory that buckling began at some flat spot on the cylinder, and for this reason small initial deviations from the perfect cylindrical shape were assumed to exist at the beginning of the loading. The results of the approximate analysis were presented in the form of a formula,

$$\sigma_{cr} = kE_L(h/r) \quad (1-63)$$

where  $E_L$  is Young's modulus of an individual veneer in the direction of the grain,  $h$  is the thickness of the plywood, and  $r$  is the mean radius of the cylinder (for the notation see Fig. 1-26). The value of the numerical factor  $k$  is to be taken from a theoretical curve which is reproduced here in Fig. 1-27. The abscissa is the ratio  $E_x/(E_x + E_\phi)$  where  $E_x$  and  $E_\phi$  are the bending moduli of strips of unit width in the axial and circumferential directions, respectively. They can be calculated from equation 1-34a.

Tests carried out by Norris and Kuenzi<sup>50</sup> at the Forest Products Laboratory with 372 yellow birch and yellow poplar cylinders showed a general agreement with the theory although there was a great deal of scatter in the individual test results. It appears that the curve can be used for predicting the buckling stress of plywood cylinders when the face grain is either axial or circumferential. Caution should be exercised in choosing the safety factors since the buckling stress of an individual cylinder may deviate considerably from the average obtained for cylinders of the same construction. This is particularly true when the parameter  $E_x/(E_x + E_\phi)$  is either smaller than 0.2 or greater than 0.8. The use of such cylinders is not recommended.

Additional tests carried out by Kuenzi<sup>51</sup> on 48 curved plywood plates showed that the buckling stress of an axially loaded curved plate is the same as that of a circular cylinder of the same construction, radius, and thickness provided the circumferential and axial dimensions of the curved plate are not smaller than the radius of curvature of the plate.

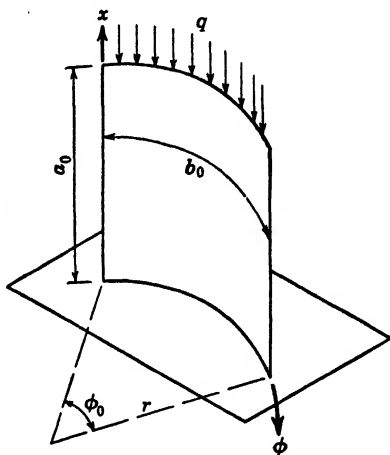


FIG. 1-26. Cylindrical Shell Subjected to Compression.



Other experimental investigations related to the buckling characteristics of plywood cylinders were reported by Kuenzi in Forest Products Laboratory Mimeographs nos. 1323 and 1501.<sup>52, 53</sup>

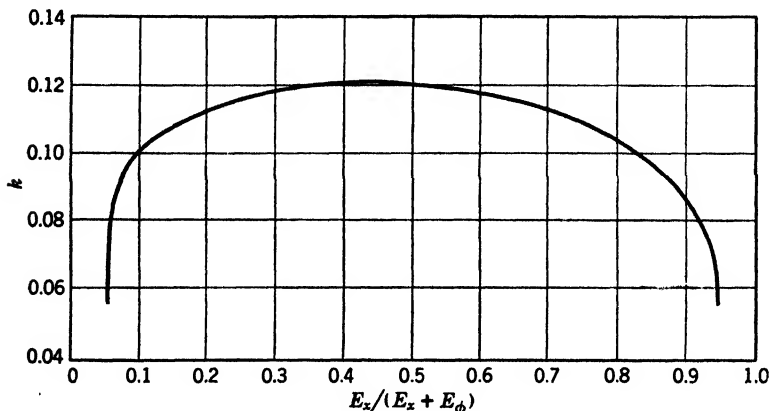


FIG. 1-27. Coefficients in Buckling Formula for Plywood Cylinder in Compression.

### TORSION

Laminated materials are often used for the walls of box girders of various shape which are subjected to torsion. In such cases the torsional rigidity of and the shear stresses in the box can be calculated from formulas presented in textbooks on *Strength of Materials* \* and *Airplane Structures*<sup>54, 55</sup> in conjunction with the methods and equations related to stresses and strains in the plane of laminated plates discussed on page 22 et seq. of this chapter.

When a bar of solid cross section is subjected to a torque and the material of the bar is orthotropic, the torsion problem of the orthotropic bar can be reduced to that of an equivalent isotropic bar provided the axis of the bar is parallel to one of the principal directions of elasticity. This will always be true when the bar is made of laminated wood or a reinforced plastic with the fibers running parallel to the axis.

The shear modulus  $G$  of the equivalent bar is the geometric mean of the shear moduli  $G_{xx}$  and  $G_{yy}$ , and the contour of its cross section can be obtained from that of the actual bar by multiplying the  $x$  co-ordinate of every point by  $\sqrt{(G/G_{xx})}$  and the  $y$  co-ordinate by  $\sqrt{(G/G_{yy})}$ , where  $G = \sqrt{G_{xx}G_{yy}}$  and  $x$  and  $y$  are the co-ordinates parallel to the two prin-

\* Reference 2, part 2, page 278.

principal directions of elasticity lying in the plane of the cross section while  $z$  is the co-ordinate parallel to the axis of the bar. The angle of twist and the warping of the cross section of this equivalent isotropic bar are the same as those of the actual orthotropic bar. They can be calculated from formulas developed for isotropic bars in *Strength of Materials*.<sup>\*</sup> On the other hand, the shear stresses calculated for the equivalent isotropic bar from the classical formulas must be transformed by multiplying shear stress components parallel to  $x$  by the factor  $\sqrt{(G_{xz}/G)}$  and those parallel to  $y$  by  $\sqrt{(G_{yz}/G)}$ .

The afore-mentioned connections were established by St. Venant. They are described in Love's *Theory of Elasticity*.<sup>56</sup> A simple presentation of the problem was given recently by Edgar Reissner<sup>57</sup> who used the formulas obtained for orthotropic bars of solid rectangular section in determining experimentally the shear moduli of Jablo improved laminated wood.

## THE STRENGTH AND STIFFNESS OF SANDWICH-TYPE STRUCTURAL ELEMENTS

### CHARACTERISTICS OF SANDWICH CONSTRUCTION

Sandwich construction is that kind of laminated construction which is characterized by the use of comparatively heavy and strong outer layers, denoted as the faces, and one or more very light and weak inner layers, designated as the core.<sup>†</sup> The rather obvious purpose of this construction is to place the strong main carrying elements far apart in order to obtain a large moment of inertia of the cross section with the ensuing benefits of high strength and rigidity. This distance is maintained by means of the core which, sandwiched between the faces, contributes little directly to the load-carrying capacity of the structure but at the same time adds relatively little weight to it. Typical materials used for faces are plywood, aluminum alloy, stainless steel, Papreg, and Fiberglas fabric, and for the core balsa wood, synthetic foams, and grids of wood or impregnated fabric.

Early investigations disclosed that the bending rigidity and the buckling load of sandwich structural elements are considerably smaller than may be anticipated on the basis of the conventional formulas of *Strength of Materials*. The reason is the small shearing rigidity of the relatively thick core. Consequently, the theory of sandwich construction must

<sup>\*</sup> Reference 2, part 1, page 261, and part 2, page 265.

<sup>†</sup> See Chapter 20 for a discussion of the materials employed in faces and cores of sandwich construction.

take into account shearing deformations which are usually neglected in other engineering calculations. Moreover the small extensional rigidity of the core permits relative displacements of the two faces which under certain conditions may result in a particular kind of instability. These characteristic problems of sandwich construction are discussed in the present section.

The theory of sandwich construction has been developed since the outbreak of the Second World War mainly in connection with aeronautical engineering. The suitability of sandwich-type elements for major structural components of aircraft was generally acknowledged after the structural details of the Mosquito fighter-bomber, built by the de Havilland Aircraft Company, were made public. Naturally wartime restrictions hampered the communication of information of military value, and thus research men often investigated problems of the strength and stability of sandwich structures with no knowledge of similar work being carried on elsewhere. In the following articles an effort is made to give due credit to all the independent workers in the field as far as is possible on the basis of the information available at present.

#### THE BENDING OF SANDWICH-TYPE BEAMS

This problem was treated by March and Smith<sup>58</sup> as an application of a method developed by March<sup>15</sup> for the calculation of the deflections of plywood strips. The two faces and the core were considered as orthotropic plates in a state of plane strain. The differential equations of equilibrium and compatibility were solved by the introduction of stress functions, and the conditions of continuity of displacements and stresses at the boundaries of faces and core were observed. The end deflection  $d$  of the cantilever beam was found to be (for the symbols see Fig. 1-28):

$$d = \frac{WL^3}{3EI} (1 - \mu_{12c}\mu_{21c}) \left(1 + \frac{1}{4} \frac{h^2}{L^2} e\right) \quad (1-64)$$

where

$$\begin{aligned} 2e = & \frac{\beta_f}{\alpha_f} \left[ 1 - 3 \left( \frac{c}{h} \right)^2 + 2 \left( \frac{c}{h} \right)^3 \right] + \frac{\beta_c}{\alpha_c} \left[ 3 \left( \frac{c}{h} \right)^2 - 2 \left( \frac{c}{h} \right)^3 \right] \\ & + \frac{1}{\alpha_f G_f} \left[ 2 - 3 \left( \frac{c}{h} \right) + \left( \frac{c}{h} \right)^3 \right] \\ & + \frac{1}{\alpha_c G_c} \left[ 3r \left( \frac{c}{h} \right) - 3r \left( \frac{c}{h} \right)^3 + 2 \left( \frac{c}{h} \right)^3 \right] \end{aligned} \quad (1-65)$$

and

$$\alpha = \frac{1}{E_1} (1 - \mu_{12}\mu_{21}) \quad \beta = \frac{1}{E_1} (\mu_{12}\mu_{23} + \mu_{13}) \quad (1-66)$$

$$r = \alpha_c / \alpha_f$$

Moreover,  $EI$  is the bending rigidity as calculated from equations 1-34 to 1-36.

In most cases an excellent approximation to equations 1-64 to 1-66 may be had if the following simplified expressions are used:

$$d = \frac{WL^3}{3EI} \left( 1 + \frac{1}{4} \frac{h^2}{L^2} e \right) \quad (1-67)$$

$$2e = \frac{E_{1f}}{G_f} \left[ 2 - 3 \left( \frac{c}{h} \right) + \left( \frac{c}{h} \right)^3 \right] + \frac{E_{1c}}{G_c} \left[ 3r \left( \frac{c}{h} \right) - 3r \left( \frac{c}{h} \right)^3 + 2 \left( \frac{c}{h} \right)^3 \right] \quad (1-68)$$

where

$$r = E_{1f} / E_{1c} \quad (1-69)$$

The theory was compared by Kommers<sup>59</sup> with experiments carried out at the Forest Products Laboratory. Tests were made with 96 beams having faces of yellow poplar veneer and a core of balsa wood. The

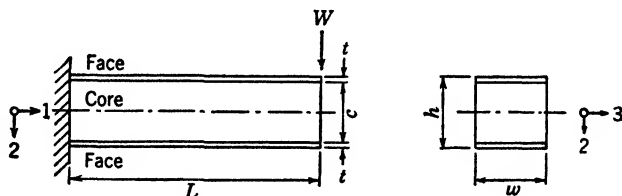


FIG. 1-28. Sandwich Beam.

grain of the faces coincided with direction 1, the grain of the core in some specimens with direction 1, and in others with direction 3. The calculated correction factor for deflections  $[1 + (1/4)(h/L)^2 e]$  varied from 1.010 to 3.50. Good agreement was found between theory and experiment, the maximum deviations of the predicted from the experimental deflection being  $-18.3$  per cent and  $+11.3$  per cent.

Another formula for the end deflection of a cantilever sandwich beam having a very light isotropic core and strong isotropic faces was derived by Hoff and Mautner.<sup>60</sup> The differential equation of the problem was obtained by the variational method from the essential portions of the strain energy stored in the beam during deformations, namely,

the strain energy of extension and bending of the faces and the strain energy of shear of the core. The differential equation was integrated and the end deflection  $d$  of the cantilever expressed in the form (for the symbols see Fig. 1-28)

$$d = \psi \frac{WL^3}{3EI} \quad (1-70)$$

where

$$\psi = 1 + C \frac{(EI)_1}{2(EI)_f} \quad (1-71)$$

and

$$C = \frac{3}{p^2 L^2} \left( 1 - \frac{\tanh pL}{pL} \right) \quad (1-72)$$

Moreover,

$$p^2 = \frac{Gcw}{EI^*} \quad (1-73)$$

$$EI^* = \frac{(EI)_1(2EI)_f}{(EI)_1 + 2(EI)_f} \quad (1-74)$$

The symbols expressing rigidities have the following meaning:

$$EI_1 = \left(\frac{1}{2}\right)tw(c+t)^2E_f$$

is the bending rigidity of the two faces when each face is thought of as being concentrated along its own horizontal centroidal axis;

$$2(EI)_f = \left(\frac{1}{6}\right)t^3wE_f$$

is the bending rigidity of the two faces when they are thought of as not being connected to each other by the core;

$$EI = EI_1 + 2(EI)_f$$

is the total bending rigidity of the sandwich beam if the bending rigidity of the core is neglected.

The value of  $C$  is plotted against the parameter  $pL$  in Fig. 1-29.

The following particular cases deserve attention:

(a) When  $pL < 0.1$ ,

$$d = WL^3/3(2EI)_f \quad (1-75)$$

Consequently, when the shearing rigidity of the core is very small, the sandwich beam deflects like a beam consisting only of the two faces.

(b) When  $pL > 100$ ,

$$d = \frac{WL^3}{3EI} + \frac{WL}{Gb_w} \left( \frac{EI_1}{EI} \right)^2 \quad (1-76)$$

Since in most cases  $(EI)_1$  differs but little from  $EI$ , the deflection is simply the sum of the bending deflection and the shearing deflection when  $pL > 100$ .

(c) When  $pL$  approaches infinity,

$$d = WL^3/3EI \quad (1-77)$$

The deflection is the simple bending deflection of the Euler-Bernoulli theory when the core is infinitely rigid in shear.

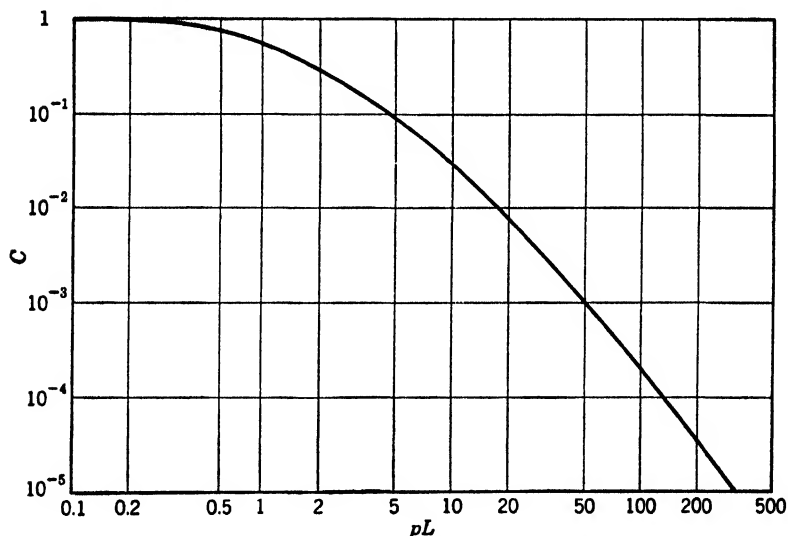


FIG. 1-29. Factor in Calculation of Deflection of Sandwich Beams.

The theory was compared with the results of experiments carried out by the staffs of the Polytechnic Institute of Brooklyn and Skydyne Inc.<sup>60</sup> Thirty-six beams were tested, some of which had a cellular cellulose-acetate core, and the others a balsa wood core. In the latter the fibers were perpendicular to the faces; that is, they were parallel to direction 2 in Fig. 1-28. The face material was 24 ST Alclad in all the specimens. Good agreement was found between theory and the results of experiments.

The theories developed by March and Smith and by Hoff and Mautner are in good agreement in the entire range of practical interest in spite of the considerable difference in the form of the equations.

The results obtained for cantilevers can also be used for simply supported beams if  $W$  is replaced by  $W/2$  and  $L$  by  $L/2$  in the formulas. The correctness of this procedure can be ascertained by inspection of

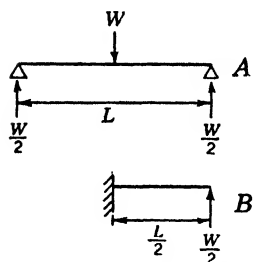


FIG. 1-30. Comparison of Simply Supported Beam with Cantilever.

Fig. 1-30 where the middle deflection of the simply supported beam ( $A$ ) is the same as the end deflection of the cantilever ( $B$ ). In other cases of loading, as for instance by distributed loads, the formulas quoted give at least an indication of how much greater deflections can be expected with sandwich-type beams than with conventional beams of equal bending rigidity.

The efficiency of a beam can be defined in several ways. One measure of the efficiency is the bending rigidity obtainable with a given weight of the material. In the case of very long beams, or when the bending moment is not accompanied by a shear force, the deflections of the beam can be calculated from the equation,

$$d = WL^3/3EI \quad (a)$$

where, with the notation of Fig. 1-28, the bending rigidity is

$$\begin{aligned} EI &= [Ec^3 + E_f(h^3 - c^3)](w/12) \\ &= (wh^3/12)[E_f - R^3(E_f - E_c)] \end{aligned} \quad (b)$$

and

$$R = (c/h) \quad (1-78)$$

The average density  $D$  of the sandwich beam is

$$D = D_f - R(D_f - D_c) \quad (c)$$

where  $D_f$  is the density of the faces and  $D_c$  that of the core.

If one is interested in designing the most efficient strip of unit width and is not restricted as far as the depth  $h$  of the beam is concerned, a fair comparison between beams of different materials and  $b/h$  ratios may be obtained by making the depth of each beam inversely proportional to the average density of its materials. Then the bending rigidity of these beams of equal weight will be proportional to the quantity,

$$Q = \frac{[E_f - R^3(E_f - E_c)]}{[D_f - R(D_f - D_c)]^3} \quad (d)$$

## The Bending of Sandwich-Type Plates and Shells 65

The ratio  $R$  has its optimum value when  $Q$  is a maximum. Differentiating  $Q$  with respect to  $R$  and setting the differential coefficient equal to zero, one obtains \*

$$R_{opt} = \sqrt{\frac{1 - (D_c/D_f)}{1 - (E_c/E_f)}} \quad (1-78a)$$

Since in sandwich construction usually both  $E_c/E_f$  and  $D_c/D_f$  are small quantities, equation 1-78a reduces to

$$R_{opt} \simeq 1 - \left(\frac{1}{2}\right) \left[ \frac{D_c}{D_f} - \frac{E_c}{E_f} \right] \quad (1-78b)$$

In many applications  $E_c/E_f$  is small compared to  $D_c/D_f$ . If it is neglected, the optimum ratio  $R_w$  of the weight of the core to the total weight of the sandwich becomes <sup>62</sup>

$$R_w = \frac{RD_c}{RD_c + (1 - R)D_f} = \frac{2 - (D_c/D_f)}{3 - (D_c/D_f)} \quad (1-78c)$$

Consequently,  $R_w$  is approximately equal to  $\frac{2}{3}$  when the ratio  $D_c/D_f$  is small.

As was mentioned earlier, these derivations are correct only when the shear deformations are negligible. When the shear forces are large compared to the bending moments, the core thickness must be reduced and the face thickness increased in order to obtain the maximum efficiency of the sandwich beam.

The normal and shear stresses in sandwich beams can be computed from the equations developed on page 38 for laminated beams. When the shear force is large and the shearing rigidity of the core small, the results so obtained may be considerably in error. In such cases recourse may be had to the publications mentioned in references 58 and 60.

### THE BENDING OF SANDWICH-TYPE PLATES AND SHELLS

Comparatively little work has been published as yet regarding the bending of sandwich-type plates and shells. In a recent paper Eric Reissner,<sup>62</sup> starting out from his earlier work <sup>63</sup> concerning the effect of transverse shear deformations in plate theory, developed differential equations for transversely loaded sandwich plates. He solved the differential equations for the case shown in Fig. 1-31. The plate of length

\* This formula was developed by H. C. Engel and W. W. Troxell in an internal report of the Glenn L. Martin Company. Graphs derived from the formula are presented in reference 61.



$L$  is fixed as a cantilever along the edge  $x = 0$  and loaded along edge  $x = L$  with a transverse load  $W$  distributed according to the equation,

$$V_x = \frac{W}{2a} \left\{ 1 + \frac{\mu}{1 + \mu} \left[ \frac{(a/k) \cosh (y/k)}{\sinh (a/k)} - 1 \right] \right\} \quad (1-79a)$$

where  $V_x$  is the shear per inch width of the plate,

$$k^2 = \left(\frac{1}{2}\right)t(t + c)(G_{\text{face}}/G_{\text{core}}) \quad (1-79b)$$

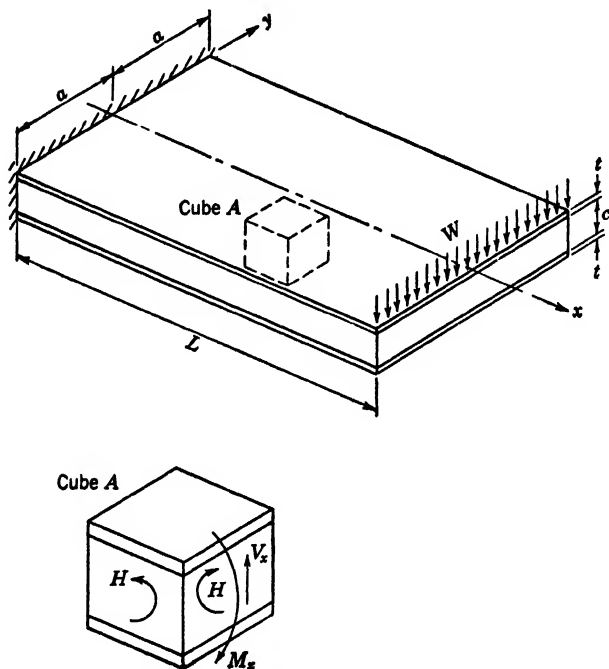


FIG. 1-31. Cantilever Sandwich Plate.

and  $\mu$  is Poisson's ratio of the face material. It may be mentioned that the equation gives an almost uniform distribution of the load along the edge in most practical problems. In the theory it is assumed that the thickness  $t$  of the faces is small, the shear load is carried entirely by the core, and the bending and twisting moments are resisted solely by the faces. Then the distribution of  $H$ , the twisting couple per inch width of the plate, can be given as

$$H = \frac{W}{2} \frac{-\mu}{1 + \mu} \left[ \frac{y}{a} - \frac{\sinh (y/k)}{\sinh (a/k)} \right] \quad (1-79c)$$

## The Bending of Sandwich-Type Plates and Shells 67

The bending moment in any section  $x$  is naturally

$$M_x = \frac{WL}{2a} \left( \frac{x}{L} - 1 \right) \quad (1-79d)$$

The transverse shear stress in the core is

$$\tau_c = V_x/c \quad (1-80a)$$

This is also the shear stress transmitted from the core to the faces. The shear stress in the faces is

$$\tau_f = \frac{H}{(c+t)t} \quad (1-80b)$$

It may be noted that  $\tau_f$  vanishes when  $y = 0$  and  $y = \pm a$ , and is a maximum when  $y = \eta$  where  $\eta$  is defined by the equation,

$$\frac{\eta}{a} = 1 - \frac{\ln(a/k)}{(a/k)} \quad (1-80c)$$

The deflections  $w$  of the plate are given by

$$w = \frac{WL^3}{(1-\mu^2)E_f I} \left\{ \left( \frac{1}{2} \right) (x/L)^2 - \left( \frac{1}{6} \right) (x/L)^3 - (\mu/2)(y/L)^2 [1 - (x/L)] \right. \\ \left. + 2(k/L)^2 \left[ 1 + \frac{\mu(a/k)}{\sinh(a/k)} \right] (x/L) \right\} \quad (1-81)$$

where the moment of inertia  $I$  of the section is

$$I = 2a[(t/2)(t+c)^2 + (t^3/6)] \quad (1-81a)$$

Because of St. Venant's principle the results can be used also in cases in which the load  $W$  is applied differently from the distribution according to equation 1-79a, provided that the length  $L$  of the plate is great as compared to its width  $2a$ .

The bending of a circular sandwich cylinder was investigated by Leggett and Hopkins.<sup>64</sup> When a very long nonreinforced cylinder is under the action of a constant bending moment, it is likely to flatten so that its originally circular cross section is transformed into an ellipse. In many structures a large amount of flattening is not permissible, and for this reason knowledge of the connection between flattening and normal stress is useful. This connection can be presented in the following form:

$$\sigma_f = E_f \left(1 - 2 \frac{d}{R}\right) \sqrt{\frac{d}{R} \frac{c+t}{c}} \sqrt{\frac{12K}{(1+2K) \left[ \left(\frac{R}{c}\right)^2 + \frac{4}{1-\mu} K \right]}} \quad (1-82)$$

where

$$K = \frac{E_f t}{E_c c} \quad (1-83)$$

and  $\sigma_f$  is the maximum stress in the face,  $E_f$  the modulus of the face material,  $E_c$  that of the core material,  $\mu$  Poisson's ratio assumed to be 0.3 for both face and core,  $t$  the thickness of the face,  $c$  that of the core,  $R$  the radius of the cylinder, and  $d$  the maximum deflection.

Both face and core were assumed to be isotropic in the calculations, and the formula was also used for predicting the deflections of an aluminum-balsa sandwich by replacing the actual balsa by an equivalent imaginary isotropic material. When the faces are of aluminum alloy and the core is of either a low-density synthetic material or balsa, equation 1-82 can be simplified by omitting small terms:

$$\sigma_f = 2.45 E_f \frac{c+t}{R} \left(1 - 2 \frac{d}{R}\right) \sqrt{\frac{d}{R}} \quad (1-84)$$

Since the core carries comparatively little load, it is desirable to keep it thin in order to reduce the weight of the sandwich cylinder. On the other hand, the thickness  $c$  of the core has to be large enough to prevent an excessive amount of flattening when the maximum normal stress is reached in the structure. From either equation 1-82 or 1-84 the required thickness  $c$  of the core can be calculated indirectly when the maximum stress  $\sigma_f$  in the face and the permissible deflection  $d$  are known.

For a rough approximation the following simplified formula may be used:

$$\frac{d}{R} = 6 \left(\frac{\sigma_f}{E_f}\right)^2 \left(\frac{R}{c}\right)^2 \quad (1-85)$$

Consequently, the flattening increases approximately as the square of the normal stress. In a first approximation it is also proportional to the square of the ratio of the radius of the cylinder to the thickness of the core.

The calculations were carried out by Leggett and Hopkins by means of the strain energy method. The deflected shape of the cylinder was assumed in accordance with the results obtained by Brazier<sup>65</sup> who investigated the flattening of an isotropic thin-walled cylinder.

## BUCKLING OF THE FACES

It was noticed by Gough, Elam, and de Bruyne<sup>66</sup> that the faces of sandwich columns, when loaded in uniform compression were likely to buckle and develop a ripple of short wave length across the test specimen. A theoretical investigation disclosed that the phenomenon could be adequately described by considering the thin faces as beams supported by an elastic foundation, namely, the core. The calculations were carried out with the aid of earlier results obtained by Biot<sup>67</sup> and Eric Reissner,<sup>68</sup> and use was made of a theorem according to which deflections and pressure are proportional to the free surface of a semi-infinite elastic body loaded with a sinusoidally distributed load, and the factor of proportionality depends on the wave length. This theorem had been used by Eric Reissner in his calculations of the buckling of a beam which rests on an elastic foundation and is rigidly supported at uniform intervals.

In the buckling of the sandwich faces the effect of the supports need not be taken into account if the wave length is small compared to the unsupported length of the sandwich column or panel. The wave length actually observed at buckling is, therefore, that which can develop first during the process of loading, that is, which corresponds to the minimum buckling load. This minimum buckling load was calculated by Gough, Elam, and de Bruyne for eight different conditions of support. When the supporting medium extends from the face material to infinity, the buckling stress is

$$\sigma_{cr} = C\sqrt[3]{E_c^2 E_f} \quad (1-86)$$

where

$$C = \sqrt[3]{\frac{9}{4(1 + \mu_c)(3 - \mu_c)}} \quad (1-86a)$$

and  $E_c$  and  $E_f$  are Young's moduli for core and faces, respectively, and  $\mu_c$  is Poisson's ratio for the core. In the analysis it was assumed that the entire buckling load is carried by the faces so that it is equal to the cross-sectional area of the faces multiplied by the buckling stress given in equation 1-86. This is a reasonable assumption when the core is very weak. The core is considered isotropic so that its shear modulus satisfies the relationship,

$$G_c = \frac{E_c}{2(1 + \mu_c)} \quad (a)$$

The constant  $C$  is given below for the limiting values of  $\mu_c$ :

## The Strength of Laminates

$$C = 0.542 \quad \text{when} \quad \mu_c = 0.5$$

$$C = 0.63 \quad \text{when} \quad \mu_c = 0$$

The wave length  $L$  predicted by the theory is

$$L = 2\pi t \sqrt[3]{\frac{(1 + \mu_c)(3 - \mu_c)}{12}} \sqrt[3]{\frac{E_f}{E_c}} \quad (1-87)$$

Since in the tests  $E_f/E_c$  was of the order of 1000, equation 87 predicted a wave length of the order of 40 times the thickness of each face.

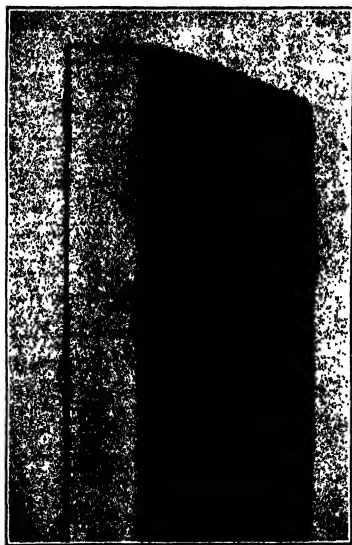


FIG. 1-32. Symmetric Ripple, Edge View.

An important arrangement considered by Gough, Elam, and de Bruyne is the one in which two equally loaded faces are separated by a core of finite thickness. The buckling stress in this case cannot be expressed by a simple formula but it was presented graphically in the publication. However, the curves do not represent accurately the actual conditions encountered in sandwich structural elements since the antisymmetric type of deformation assumed in the theory has not been observed in experiments. Moreover, the authors investigated long-wave-type buckling also by the same method of approach and arrived at the inconsistent conclusion that a finite compressive load is required to cause an infinitely long sandwich beam to buckle.

Williams, Leggett, and Hopkins<sup>69</sup> explained this inconsistency in the work of Gough, Elam, and de Bruyne. The latter had assumed that the faces were inextensional, whereas in long-wave buckling of the Euler type the extensions attain great importance. Williams, Leggett, and Hopkins concluded, however, that the theory was fully adequate for predicting the short-wave ripple type of instability. Gough, Elam, and de Bruyne carried out a great number of careful experiments with specimens corresponding to three different kinds of support using onazote, an expanded ebonite, for the supporting medium, and spring steel, aluminum alloy, magnesium alloy, and birch plywood for the faces. Eighty test specimens were reported in the paper which showed a reasonably satisfactory agreement with the theory.

The theory of reference 66 was again checked independently by van der Neut.<sup>70</sup> The differential equations were developed with due consideration of the stretching of the faces, and all the practically important cases treated by Gough, Elam, and de Bruyne were recalculated. Van der Neut concluded that the earlier theory was accurate enough for predicting the short-wave ripple-type buckling of a sandwich column having a very light core, but it had to be modified for heavier cores as well as for long-wave-type buckling.

In the experiments carried out by Hoff and Mautner<sup>71</sup> two distinct types of buckling of the faces were observed. They were designated as the symmetric and the skew ripple, respectively, and are shown in Figs. 1-32, 1-33, and 1-34. Approximate strain-energy theories were developed for both types of instability, and a rigorous solution, similar to those obtained by Gough, Elam, and de Bruyne, was established for the symmetric ripple. The authors concluded that:

1. The agreement between the buckling stresses according to the rigorous and the approximate solutions of the symmetric case was satisfactory.

2. The symmetric ripple corresponded to the smaller buckling stress when the  $(c/t)$  ratio was large,  $c$  being the thickness of the core and  $t$  the thickness of each face.

3. The skew ripple corresponded to the smaller buckling stress when the  $(c/t)$  ratio was small; and

4. The minimum buckling stress was sufficiently constant over the entire practical range of  $(c/t)$  ratios to warrant the use of the following simple formula for predicting conservatively the critical stress,

$$\sigma_{cr} = \left(\frac{1}{2}\right) \sqrt[3]{E_f E_c G_c} \quad (1-88)$$

where  $E_f$  is Young's modulus of the face material for bending,  $E_c$  Young's modulus of the core material for tension and compression perpendicular to the plane of the panel, and  $G_c$  the shear modulus of the core associated



FIG. 1-33. Skew Ripple, Edge View.

with the directions of the load and of the perpendicular to the panel. Equation 88 is valid for orthotropic faces and core since in the strain-energy theory isotropy was not assumed.

Hoff and Mautner tested 51 flat sandwich panels having Papreg faces and a cellular cellulose acetate core. According to the theory, the

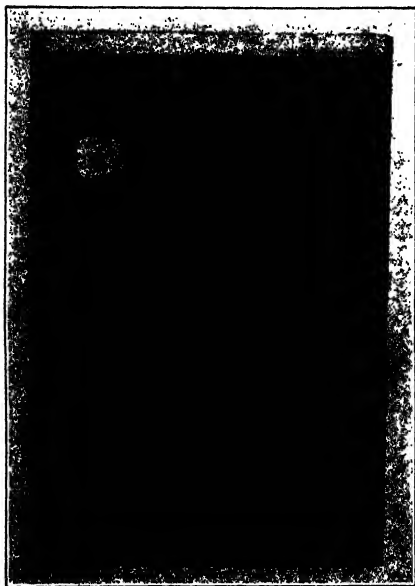


FIG. 1-34. Skew Ripple, Face View.

specimens had to develop the symmetric ripple when the  $(c/t)$  ratio was greater than about 20, and the skew ripple when the ratio was smaller than this value. Out of the 51 specimens tested 50 buckled in agreement with the theory. Moreover, no systematic variation of the buckling stress with  $(c/t)$  ratio was observed, but the scatter of the experimental values was considerable. It was concluded that equation 1-88 gives a satisfactory conservative estimate of the critical stress corresponding to both the symmetric and skew ripple instabilities of sandwich structural elements.

Equation 1-88 can be used for establishing requirements regarding the elastic properties of

the core needed to preclude ripple-type instability until the maximum working stress is reached in the faces. Substitution of  $\sigma_{max}$  for  $\sigma_{cr}$  and solution for  $\sqrt{E_{c\ min} G_{c\ min}}$  yield

$$\sqrt{E_{c\ min} G_{c\ min}} = 2.83 \sqrt{\frac{\sigma_{max}^3}{E_f}} \quad (1-89)$$

If the core is assumed to be isotropic and  $G_c = (\frac{1}{2})E_c$ , the following minimum values are obtained for Young's modulus of the core:

$E_{c\ min} = 6520$  psi when the faces are of Papreg

$E_{c\ min} = 10,120$  psi when the faces are of 24 ST aluminum alloy

$E_{c\ min} = 10,720$  psi when the faces are of steel

The maximum compressive working stresses for these materials were chosen as 20,000 psi, 40,000 psi, and 60,000 psi, respectively.

The condition of sandwich buckling was recently subjected to a much more rigorous analysis by Goodier.<sup>72</sup> He started out from the observation that the critical strain of a sandwich panel consisting of two faces connected by a core perfectly rigid in shear is three times as great as the critical strain of the core of the same panel when the faces are absent. Consequently, omission of an investigation of the stability of the core amounts to the assumption that the core can stabilize the faces until its own stability limit is far exceeded, provided the sandwich panel buckles under the highest theoretically possible load. In Goodier's buckling theory the stability of the core is given due consideration, but the buckling criterion obtained is involved and has not yet been evaluated numerically. It is anticipated that Goodier's work will attain practical importance in the case of sandwich panels which are so efficiently constructed that their column or plate-type buckling load is not reduced materially by the limited shearing rigidity of the core, and which have cores sufficiently rigid to prevent the occurrence of the ripple-type instability until the highest theoretically possible buckling load is closely approached.

Some of the experience gained by Chance-Vought Aircraft with aluminum-alloy-cross-grain-balsa sandwich construction was reported recently in two papers written by Wan<sup>73</sup> and Gibbons,<sup>74</sup> respectively. Ripple-type instability was observed at Chance-Vought Aircraft with Metalite plate, that is, plates having aluminum alloy for faces and balsa wood with the grain perpendicular to the faces for the core, at stresses smaller than those predicted by equation 1-88. It is not easy to determine the reason for this early buckling, but it might have been caused by the Goodier effect or by an early yielding of the face material since the buckling stress was high, ranging from 54,000 to 66,000 psi. At Chance-Vought Aircraft a theory was developed by Wan at the suggestion of Donnell in which failure was explained by the limited strength of the core material and the initial waviness of the faces. Any original deviation from the perfect plane form increases as the compressive end load is increased, until the stretching of the transverse fibers of the core causes rupture. Thus failure is calculated from a problem of equilibrium and not handled as an instability phenomenon. Of course the magnitude of the initial deviations from the theoretical plane is not known. It was assumed as a function of the physical quantities involved in a manner first suggested by Donnell,<sup>75</sup> and the function included a constant which was determined from test results.

On the basis of this theory the stress at which ripples appear on the surface of the sandwich panel depends on the strength as well as the



rigidity of the core. Figure 1-35, taken from Gibbons' paper, contains curves of constant critical stress drawn in a diagram the abscissa of which is the modulus of the core and the ordinate the tensile strength of the core. The graph was developed for 75 ST aluminum-alloy faces and end-grain balsa core. It can be used to determine the minimum strength and stiffness requirements of an efficient balsa core. Because

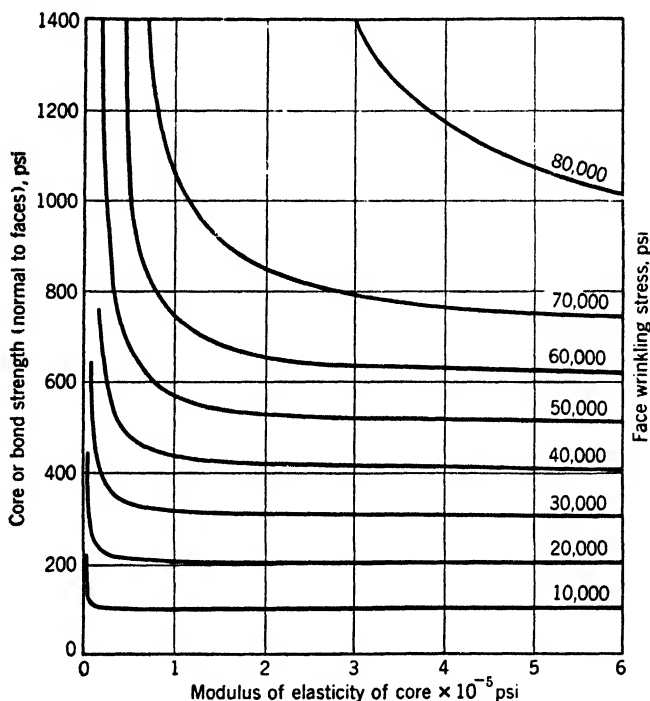


FIG. 1-35. Wrinkling Stress of Metalite.

of the empirical constant involved, the diagram should not be relied on when the sandwich panel is constructed of other materials. It gives too low values for the 24 ST aluminum-alloy-cellular-cellulose-acetate panels investigated by Hoff and Mautner, and for the aluminum-alloy-honeycomb panels tested by Troxell and Engell which are discussed on page 80. With the former, the modulus of the core was about 2000 psi, the strength of the core about 60 psi, and the buckling stress in a number of specimens higher than 12,000 psi. With the latter the effective modulus of the core was 20,000 psi, the effective strength of the core 325 psi, and the buckling stress in a number of 24 ST specimens higher than 40,000 psi, and in a number of 75 ST specimens about 60,000 psi.

Equation 88 was found to predict the buckling stress of these panels with a reasonable degree of accuracy.

### BUCKLING OF COLUMNS

A sandwich column will fail as a Euler column if the elastic properties of its core are so chosen as to preclude the ripple-type instability of the faces at lower values of the applied compressive stress than that corresponding to column failure. On the other hand, the Euler-type buckling will be greatly influenced by the small shearing rigidity of the core. This effect may be accounted for by computing the buckling load from the Engesser formula, equation 1-55, if the faces are sufficiently thin. When this is not the case, a more accurate theory is needed.

Such more accurate theories were developed independently by Williams, Leggett, and Hopkins,<sup>69</sup> by van der Neut,<sup>70</sup> and by Hoff and Mautner.<sup>60</sup> All three derivations led to almost identical results. The first three authors, after a rigorous analysis which resulted in somewhat cumbersome expressions, derived an approximate strain-energy theory which they found accurate enough for practical applications. In it the displacements of the beam were assumed to consist of a portion due to bending and one due to shear, and the ratio of the two was determined from the requirement that the buckling load be a minimum. The result of this approximate theory can be transformed to read

$$P_{cr} = \frac{G_c c w (P_1 + P_2 + P_c) + P_2 \left[ 4P_c + \left( \frac{c}{c+t} \right)^2 P_1 \right]}{P_c + \left( \frac{c}{c+t} \right)^2 P_1 + G_c c w} \quad (1-90)$$

where  $c$  is the thickness of the core,  $t$  that of each face,  $w$  the width of the column, and

$$P_1 = (\pi^2/2)(c+t)^2 t w E_f / L^2$$

is the buckling load of a column whose faces are connected by a core perfectly rigid in shear, provided  $t^3$  is considered negligibly small;

$$P_2 = (\pi^2/6)t^3 w E_f / L^2$$

is the buckling load of the two faces considered as independent columns (the core having no shearing rigidity);

$$P_c = (\pi^2/12)c^3 w E_c / L^2$$

is the buckling load of a column consisting of the core only;  $E_f$ ,  $E_c$ , and  $G_c$  are Young's moduli for the faces and the core, respectively, and the

shear modulus of the core;  $L$  is the distance between inflection points. ( $L$  is equal to the length of the column when its ends are pin-jointed and equal to one-half the length when the ends are rigidly fixed.)

In the work carried out by van der Neut, and by Hoff and Mautner the capacity of the core to carry axial loads was neglected. This assumption is fully justified when the core is a synthetic foam, or balsa wood having its grain perpendicular to the faces, as is usual in American airplane structures. The formula previously developed is preferable when the balsa core has its grain in the axial direction, as was the war-time practice in the British aircraft industry. Van der Neut solved the differential equation of the problem derived from a consideration of the equilibrium conditions, stress-strain relations, and the compatibility and boundary conditions. He simplified the solution obtained for the case when the wave length is great and arrived at a result which, except for a factor  $c/(c + t)$ , is fully equivalent to that given by Hoff and Mautner. The latter two authors started out from the essential portions of the strain energy stored in the column at buckling, in which they included the extensional and bending strain energies of the faces, the shear strain energy of the core, and that part of the extensional strain energy of the core which is associated with extensions perpendicular to the faces. From the strain energy the differential equations of the problem were derived by means of the variational principle. Independent equations and boundary conditions were obtained for the short-wave symmetric ripple and the long-wave Euler-type instability. Solution of the latter gave

$$P_{cr} = \frac{P_1 P_2 + G_c c w P_1 + G_c c w P_2}{P_1 + G_c c w} \quad (1-91)$$

where the meaning of the symbols is the same as in equation 1-90.

The following particular cases are of interest:

(a) When the bending rigidity of each face is negligibly small,  $P_2 = 0$  and equation 1-90 reduces to

$$P_{cr} = \frac{(P_1 + P_c) G_c c w}{(P_1 + P_c) + G_c c w} \quad (1-90a)$$

while equation 1-91 becomes

$$P_{cr} = \frac{P_1 G_c c w}{P_1 + G_c c w} \quad (1-91a)$$

Equation 1-90a is the same as the Engesser formula, and equation 1-91a is also identical with it in the case when the modulus of elasticity of the core is negligibly small in the axial direction.

## The Buckling of Sandwich-Type Plates and Shells 77

(b) When the shearing rigidity  $G_{scw}$  of the core is very large equation, 1-90 becomes

$$P_{cr} = P_1 + P_2 + P_c \quad (1-90b)$$

and equation 1-91 reduces to

$$P_{cr} = P_1 + P_2 \quad (1-91b)$$

Consequently, the buckling load is the Euler load when the core is infinitely rigid in shear.

(c) When the core is very weak,  $G_{scw} = 0$  and  $P_c = 0$ , both equations 1-90 and 1-91 reduce to the same expression:

$$P_{cr} = P_2 \quad (1-90c)$$

In this case the load carried by the sandwich column is the sum of the loads carried independently by the two faces.

Tests carried out with 50 columns having 24 ST Alclad faces and either cellular cellulose-acetate or edge-grain balsa core were reported by Hoff and Mautner.<sup>60</sup> Although there was a considerable amount of scatter, reasonable agreement could be found between calculated and measured critical loads. The average experimental values were about 80 per cent of those predicted by theory, and the maximum experimental values were generally quite close to the theoretical values. A few individual specimens, poorly constructed or centered, failed at about one-half the theoretical buckling load.

### THE BUCKLING OF SANDWICH-TYPE PLATES AND SHELLS

The problem of the buckling stress of rectangular sandwich panels in edgewise compression was solved independently by Leggett and Hopkins<sup>64</sup> and by van der Neut.<sup>76</sup> Leggett and Hopkins made use of the same type of approximate strain-energy analysis as was found to give sufficiently accurate results in the case of sandwich beams.<sup>60</sup> They obtained the following expression for  $p_{cr}$ , the buckling load per inch width of the panel:

$$\frac{p_{cr}}{E_c c} = \frac{\pi^2 I (1 + K) (1 + K^{-1})}{b^2 c E_c} - \frac{\pi^4 c^4 (1 + K)^2 (1 + K^{-1}) (1 + 6\delta\epsilon)^2}{72 b^4 (1 - \mu) (1 - \mu^2)} \quad (1-92)$$

where  $E_c$  is the modulus of elasticity of the core,  $\mu = 0.3$  Poisson's ratio,  $c$  the thickness of the core, and  $b$  the width of the panel. Moreover,

$$\delta = E_f / E_c \quad (1-92a)$$

$$\epsilon = t / c \quad (1-92b)$$

$$K = (b/L)^2 \quad (1-92c)$$

$$I = \frac{E_c c^3}{12(1 - \mu^2)} + 2tE_f \frac{3(c + t)^2 + t^2}{12(1 - \mu^2)} \quad (1-92d)$$

and  $E_f$  is the modulus of elasticity of the face,  $t$  the thickness of the face, and  $L$  the length of a half-wave at buckling.  $K$  has to be chosen so as to make  $p_{cr}$  a minimum, but the total length of the panel must naturally be an integral multiple of the wave length. According to Leggett and Hopkins,  $K = 1$  generally gives a good approximation.

Van der Neut extended his work related to the buckling of sandwich beams, but had to make additional assumptions in order to simplify the calculations. In particular, he took the core to be inextensional in the direction perpendicular to the faces and assumed the displacements in a plane parallel to the faces of any point in the core as a linear function of the co-ordinate perpendicular to the faces. The accuracy of these assumptions was checked and found satisfactory by recalculating the buckling load of the beam. The result obtained for the panel is

$$\frac{p_{cr}}{D} = \left(\frac{\pi c}{b}\right)^2 A \left[ \frac{1}{3} \frac{K^2}{1 - (1/k)^2} + \frac{1}{1 + (1/k)^2} \frac{1 + (A/6K)}{A} \right] \quad (1-93)$$

where

$$D = \frac{E_f t}{1 - \mu_f^2} \quad (1-93a)$$

$$k = (1 - \mu_c) \left(\frac{b}{\pi c}\right)^2 \frac{A}{K} \quad (1-93b)$$

$$A = \left[ \frac{(1 - \mu_f^2)E_c}{(1 - \mu_c^2)E_f} \right]^{3/8} \quad (1-93c)$$

$$K = \left[ \frac{(1 - \mu_c^2)E_f}{(1 - \mu_f^2)E_c} \right]^{1/8} \frac{t}{c} \quad (1-93d)$$

and  $\mu_c$  is Poisson's ratio for the core,  $\mu_f$  that for the face, and the other symbols have the same meaning as before. Equation 1-93 holds provided  $\pi^2(c/b)^2$  is considerably smaller than unity, which should be the case with normal sandwich panels.

The buckling load of slightly curved sandwich panels was calculated by Leggett and Hopkins<sup>64</sup> who used the same approach in this investigation as in the determination of the buckling load of flat panels. They arrived at the following formula:

$$\frac{p_{cr}}{E_c c} = \frac{\pi^2 I (1 + K)(1 + K^{-1})}{b^2 c E_c} + \frac{b^2 (1 + 2\delta\epsilon)[2K(1 + \mu) + 1]}{\pi^2 \rho^2 K(1 + \mu)[2K + 1 - \mu]} \quad (1-94)$$

The meaning of the symbols is the same as in the earlier formula of Leggett and Hopkins, and  $\rho$  is the mean radius of curvature of the two faces. Again  $K = 1$  gives a good approximation to the smallest buckling load as long as the curvature is slight.

A similar investigation by the same two authors yielded for the critical stress of a sandwich-type cylinder

$$\frac{p_{cr}}{E_c c} = \gamma - \frac{\theta}{K'^2} \quad (1-95)$$

where

$$K' = \frac{\alpha}{\sqrt{\beta} - 1} \quad (1-95a)$$

$$\alpha = \frac{6o^2(1 - \mu)}{c^2(1 + 6\delta\epsilon)} \quad (1-95b)$$

$$\beta = \frac{3\rho^2(1 - \mu)(1 + 6\delta\epsilon + 12\delta\epsilon^2)}{c^2(1 + \mu)(1 + 2\delta\epsilon)(1 + 6\delta\epsilon)^2} \quad (1-95c)$$

$$\gamma = \frac{1 + 6\delta\epsilon + 12\delta\epsilon^2}{2(1 + \mu)(1 + 6\delta\epsilon)} \quad (1-95d)$$

$$\theta = \frac{6\rho^2(1 - \mu)(1 + 2\delta\epsilon)}{c^2(1 + 6\delta\epsilon)} \quad (1-95e)$$

Leggett and Hopkins also calculated the strength to weight ratios of sandwich panels. They concluded that flat sandwich panels are slightly less and curved sandwich panels considerably more efficient in carrying compressive end loads than are conventional present-day reinforced aluminum-alloy panels of airplane structures.

## GRID SANDWICH CONSTRUCTION

It has been proposed to replace the continuous core of the sandwich panel by a grid manufactured of wood, paper, or impregnated textiles. Figure 1-36, taken from a paper by Troxell and Engel,<sup>77</sup> shows such a grid sandwich designated as the honeycomb type by the manufacturers, The Glenn L. Martin Company and the United States Plywood Corporation. The advantage of the grid core is that it can be built of a high-strength and high-stiffness material, and, nevertheless, its weight per cubic foot is small because of the interstices of the grid.

The stresses in and the stiffness of grid sandwich beams, columns, and plates can be calculated according to the principles set forth in the preceding articles. The effective extensional and shearing rigidities of the grid per square inch gross area, not net area of the grid, must be used in these calculations. As in the case of continuous core-type sandwiches, due consideration should be given to the small shearing rigidity of the construction. The ripple-type instability can occur and can be calculated from equation 1-88, provided the mesh of the grid is not too coarse. In addition, the buckling of the unsupported areas of the faces bounded by the grid must be checked.

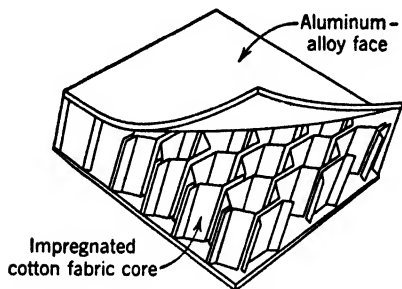


FIG. 1-36. Honeycomb Sandwich Construction.

In tests carried out at The Glenn Martin Co. with 36 honeycomb sandwich panels Engel and Troxell<sup>77</sup> found good agreement between theory and experiment. The panels had aluminum-alloy faces and a honeycomb core manufactured of cotton fabric impregnated with phenolic laminating varnish. The cells were regular hexagons of such size

that a circle of 0.43 in. diameter could be inscribed. The effective modulus of elasticity of the core perpendicular to the plane of the sandwich panel was 20,000 psi in compression, and the effective shear modulus of the core associated with one of the principal directions of elasticity in the plane of the panel and with the direction perpendicular to the panel was 8000 psi. The panels were tested as columns, with the unloaded edges unsupported. They failed in one of three ways: (1) instability as a column (Euler-type buckling); (2) buckling of the faces into the honeycomb cells; (3) ripple-type instability.

Dale and Smith<sup>77</sup> tested 15 panels having three-ply faces glued to a rectangular grid of half-notched strips of pine wood. The spacing of the strips varied between 1.28 in. and 2.58 in. The panels were tested in compression, and the unloaded edges were held straight by means of wooden side guides. All panels failed in a combination of two types of instability: (1) buckling of a rectangular panel of face between adjacent strips of wood of the core; (2) buckling of the sandwich panel as a whole.

For the latter type of instability Dale and Smith developed an approximate strain-energy theory which takes into account the small shearing rigidity of the core. They found that the buckling load  $P_s$  of the

panel can be calculated with the aid of equation 1-55, the Engesser formula,

$$P_s = \frac{P_{cr}GA^*}{P_{cr} + GA^*}$$

provided  $P_{cr}$  is the buckling load of the panel neglecting the effects of the shearing deformations. Consequently  $P_{cr}$  can be obtained from equation 1-57 by multiplication of the critical stress  $\sigma_{cr}$  of the panel by its width and thickness.  $G$  is the effective shearing rigidity of the panel per square inch of gross area and  $A^*$  the gross cross-sectional area multiplied by a numerical factor which was found to be  $1 + (3/4)(L/b)^2$  when the loaded edges were rigidly fixed and the unloaded edges simply supported. In the last expression  $L$  is the length of the panel in the direction of the load and  $b$  its width. Fair agreement was found between theory and experiment.

Other tests carried out with wood-stringer sandwich panels in edge-wise compression and shear were described by Barwell and Thurston.<sup>78</sup>

The problem of choosing the dimensions of the sandwich panel for a maximum value of the load-to-weight ratio was also given consideration in the two publications just discussed. Troxell and Engel developed comparatively simple formulas for finding the optimum value of the ratio face thickness divided by core thickness when the panel is loaded as a column and its unloaded edges are not supported. The shearing deformations were taken into account as in equation 1-55. The results of their development work are

$$\frac{2t}{c+t} = \frac{G_c}{\sigma} + \frac{RD_c}{2D_f - D_c} = \sqrt{\left(\frac{G_c}{\sigma}\right)^2 + \left(\frac{RD_c}{2D_f - D_c}\right)^2} \quad (1-96)$$

where

$$R = 1 - \sigma \frac{dE/d\sigma}{E} \quad (1-96a)$$

and  $G_c$  is the effective shearing rigidity of the core,  $D_c$  the density of the core,  $D_f$  that of the face,  $\sigma$  the maximum compressive stress applied to the faces,  $E$  the modulus of the face material at this stress, and  $dE/d\sigma$  the slope of the modulus-versus-stress curve at the same stress. Equation 1-96 can be used for finding the optimum value of  $2t/(c+t)$  for different values of the applied stress when the densities and the mechanical properties of the materials of face and core are known. With this optimum  $2t/(c+t)$  and the assumed value of  $\sigma$  the loading parameter  $P/bL$  can be determined from the formula:



$$\frac{P}{bL} = \frac{(2\sigma)(2t)/(b+t)}{\pi \sqrt{\frac{E}{\sigma}} \left(1 - \frac{2t\sigma}{(b+t)G_c}\right)} \quad (1-97)$$

When the thicknesses have to be chosen by the designer, the load to be carried by the panel and the unsupported length and width are usually known. The best ratio  $2t/(c+t)$  can then be determined from a plot of the values of this optimum ratio against the loading parameter  $P/bL$ .

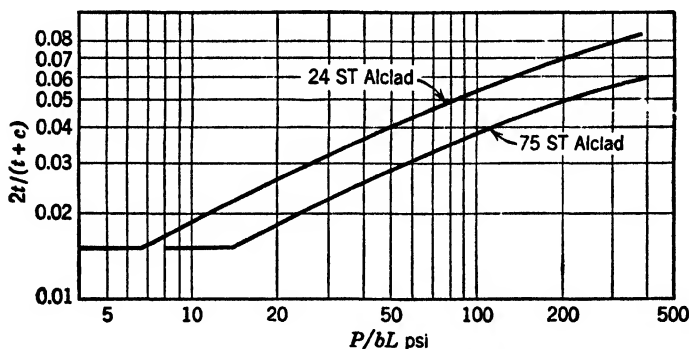


FIG. 1-37. Optimum Thickness Ratio of Honeycomb Sandwich.

Such a plot is shown in Fig. 1-37 as presented by Troxell and Engel for the particular type of honeycomb sandwich they investigated. The method of constructing such diagrams, however, is of more general validity and can be used for any type of sandwich construction.

A lengthier investigation of the optimum dimensions of the grid-type sandwich construction was carried out by Dale and Smith and is presented in ACA Report no.16.

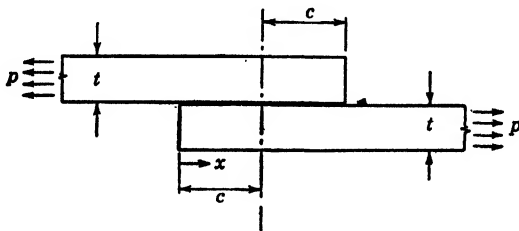


FIG. 1-38. Lap Joint.

### THE STRESSES IN GLUED JOINTS

On page 33 mention was made of the stress concentrations along the edges of laminated panels. A somewhat similar problem, namely, the

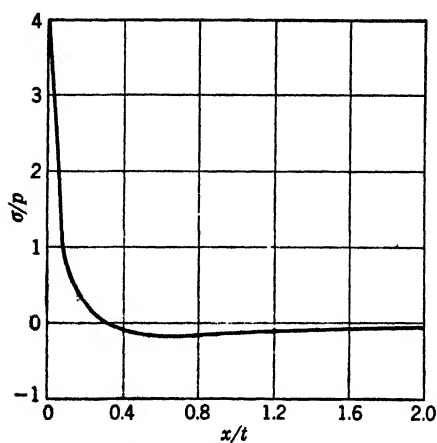


FIG. 1-39. Tearing Stress  $\sigma$  in Plywood Lap Joint.

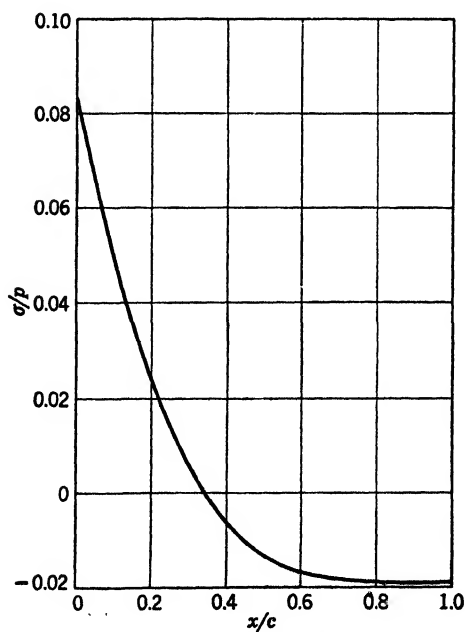


FIG. 1-40. Tearing Stress  $\sigma$  in Metal Lap Joint.

stress distribution in glued lap joints, was investigated by Goland and Reissner.<sup>79</sup>

Figure 1-38 is the edge view of two lap-jointed plates of equal thickness  $t$  which are subjected to tensile stresses  $p$  uniformly distributed over the thickness at some distance from the joint. The far ends of the plates may be considered as simply supported in order to balance the couple caused by the noncollinear load application. The problem of determining the stresses in the glue was formulated as one in plane strain, and the changes in the loads transmitted through the glue caused by the deflections of the plates were considered. The existence of large tearing stresses  $\sigma$ , that is, stresses in the glue substance perpendicular to the plane of the sheets, was discovered and their magnitude calculated for two limiting cases. In the first the glue substance is relatively inflexible compared to the plates it joins, and in the second the opposite is true. In both cases a large concentration of the tearing stresses occurs at the edge of the plate which explains the tendency of lap joints to open up unless they are otherwise secured.

Figures 1-39 and 1-40 present the distribution of the tearing stresses as calculated by Goland and Reissner. The first figure corresponds to a typical joint of plywood plates, and the second to one of aluminum-alloy sheets.

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## CHAPTER 2

### Adhesives

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#### HISTORY

The range of materials which have been used as adhesives is unusually broad and goes back to earliest recorded history. The naturally occurring gums and waxes were used by the Egyptians for the gluing together of decorative composite structures. Animal glue from hides and bones has been known as a wood adhesive for 3300 years. The application of gold leaf and the binding of pigments with egg albumen were practiced extensively as early as the 13th century and are the basis of tempera painting.

The development of adhesives for structural purposes is very recent, however, and the use of animal glue was followed by the use of casein, cassava flour, soyabean protein, and blood albumen during the period from the early 19th century to World War I. These adhesives were used almost exclusively for the bonding of wood. With the advent of synthetic-resin adhesives the technology of bonding nonmetallic surfaces made rapid strides. Phenol-formaldehyde resins were introduced by Baekeland <sup>1</sup> in 1909, but it was not until the manufacture of Tego Film in 1934 in the United States that they became commercially significant as adhesives. Urea formaldehydes as liquid sirups were introduced in 1920 when John <sup>2</sup> recognized their value as adhesives.

The growth of the plastics industry in recent years has brought a variety of bonding problems, and the use of metal and wood or plastic composite structures has placed new requirements on research ingenuity.

The development of adhesives has been largely empirical, principally because the basic nature of the forces between bonded surfaces and the adhesive have been the subject of little scientific investigation, and only a few workers have concerned themselves with this field. McBain <sup>3</sup> and



his co-workers in England, and Truax and his staff at the Forest Products Laboratory have done pioneering investigation on the fundamentals of adhesion.

As part of a program under the sponsorship of the National Advisory Committee for Aeronautics, R. C. Rinker and G. M. Kline, of the Bureau of Standards, published a survey (Technical Note 989) in August 1945, of the status of the fundamental information available on adhesives and the principles of adhesion. More recently, J. Delmonte<sup>4</sup> has discussed the theories of adhesive action in a well-documented review of the entire field of adhesives.

### THEORIES OF ADHESION

The forces which hold two surfaces adhesively bonded together are usually classified into two types: namely, mechanical and specific.

Mechanical adhesion, as the name implies, is the "keying" or physical interlocking of the irregularities and pore spaces of the surfaces to be joined. Such mechanical bonding was at one time thought to be the principal source of adhesive strength. It is becoming increasingly evident, however, that only a small part of the strength of joints made between two surfaces is due to the interlocking of pore spaces in the surfaces by the adhesive. The more recent theories indicate that the forces of adhesion which bond two surfaces are closely related to the cohesive forces which maintain the structure of solid matter, so-called specific adhesion.

The specific adhesion of the bonding medium for the surfaces to be joined is principally due to electrical and chemical forces. These may be classified as (1) electrostatic or polar bonds, (2) covalent and coordinate covalent bonds, (3) metallic bonds, and (4) van der Waals forces. All these forces operate over small distances, of the order of atomic dimensions, and, therefore, a prerequisite to proper bonding is intimate contact of the adhesive and the surface; that is, the adhesive and its solvent, if any, must wet the surfaces to be joined. For similar reasons, polar adhesives should be used for the bonding of polar surfaces, and nonpolar adhesives for bonding nonpolar surfaces.

Although the development of adhesives has been largely empirical and little fundamental work has been carried out on the theories of adhesion, some generalizations have been possible on the basis of the chemical behavior of the adhesive and the chemical susceptibility of the surface to be bonded. For example, it is usually postulated that phenol-formaldehyde bonds are made principally on the basis of hy-

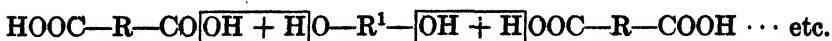
drogen bridges. Urea-formaldehyde bonds, on the other hand, are usually assumed to be via a water film interposed between the urea-formaldehyde polymer and the surface; the ureas will bond materials which contain surface hydroxyl groups to provide much stronger bonds than they will on surfaces which will not allow the bridging via a water film. Another example, perhaps, is the use of rubber cements for the bonding of copper surfaces. In this case, it is usually assumed that the sulfur contained in the vulcanizate actually makes a chemical bond with the copper. The failure of such bonds is frequently due to poor adhesion between the copper sulfide and the metal.

Thus, it can be seen that, for a particular construction, not only the adhesive characteristics but also the composition and condition of the surfaces to be bonded must be considered. These factors, together with the actual bonding conditions under which the adhesive is used, must be carefully selected in order to achieve the optimum strength characteristics of the final laminate.

#### ADHESIVE TYPES

Most of the materials used as adhesives are large molecules or polymers formed by the chemical combination of smaller molecular units. When synthetically produced, these repeating units or segments are formed by the linking together of the monomer starting material by either condensation polymerization or vinyl polymerization. If a by-product, formaldehyde, water, ammonia, hydrogen chloride, etc., is eliminated between the adjacent units during polymerization, the process is described as a condensation reaction. Any reaction which results in a bond between two molecules may be used for polymer formation, provided there are two or more functional groups per molecule. Vinyl polymerization, on the other hand, is the result of the chain reaction which is initiated when a double bond between two carbon atoms is reduced to a single bond by the formation of a radical. Thus, the polymer has the same ultimate analysis as the monomer from which it was formed since no by-products result from the reaction.

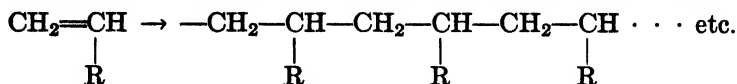
The reaction of a dibasic acid with a dihydric alcohol is typical of a condensation polymerization:



In this case, the polymer will be linear, and only long chains will be formed, but, if one of the reactants is trifunctional rather than difunc-

tional, the possibility of cross linking of the chains exists, and a three-dimensional polymer can be formed.

A typical vinyl polymerization can be represented as follows:



Although such a polymer is linear, the cross linking can be accomplished with a proportion of divinyl monomer.

The naturally occurring materials which are used as adhesives, such as the starches or proteins, are polymers of sugars and amino acids and can be considered as condensation polymers.

The structure of the various synthetic adhesive polymers is described briefly in the following paragraphs under the discussion of the individual classes of these compounds. They fall into two general classes, however, which, while not exactly defined, are recognized divisions. These are the thermoplastic and the thermosetting. As the name implies, the former may be rendered soft by heating, and the change in physical properties is reversible; the latter is set to an irreversible final form by the action of heat or catalysts or both. In general, thermoplastic polymers are linear, with few, if any, cross linkages between the chains. Thermosetting polymers are usually three-dimensional and, in final form, are highly cross-linked.

The variety and properties of synthetically produced polymers are capable of almost infinite variation. The researches of Carothers,<sup>5</sup> Flory,<sup>6</sup> Mark,<sup>7</sup> Staudinger,<sup>8</sup> and others have put the chemistry of high polymers on a systematic basis and allow to a considerable extent the prediction of the properties to be expected from the product of a given reaction.

For an excellent and readable review of the commercially important polymers, the reader is referred to *Synthetic Resins and Rubbers* by P. O. Powers, published by John Wiley & Sons, 1943.

Adhesives may also be arranged under two other classifications which overlap and are independent of the two classifications previously mentioned. These are the rigid and flexible adhesive types. In general, for laminated constructions, the rigid types, thermosetting synthetic resins such as the phenolformaldehydes, are usually preferred because of their greater durability. Flexible adhesives based on rubbers or thermoplastic polymers which are flexible have some advantages in compound constructions subject to stresses caused by the varying conditions of

service. In such cases, the ability of the bond to absorb local stress concentrations very often results in a superior over-all strength of the laminate under consideration.

Another classification which may be considered as adhesive in the broader sense is the use of solvent for the bonding of adjacent surfaces which are both soluble in the solvent and also usually completely compatible with each other. Such bonding is most frequently encountered in the field of the synthetic thermoplastic materials such as the acrylics, nitrocellulose lacquers and various vinyl polymers.

In commercial practice, adhesives are frequently a mixture or co-reaction product of different types. Thus, a thermosetting component may be used in combination with a flexible and thermoplastic component to obtain optimum performance under the conditions of service. In other cases, mixed adhesive systems are necessary to obtain proper adhesion between dissimilar construction materials in a laminate which could not be satisfactorily bonded by either adhesive component alone.

#### ANIMAL GLUE

Animal glue,<sup>9-14</sup> which belongs in the category of protein-base adhesives, is the oldest of the ordinarily used adhesives. The Egyptians understood the art of manufacturing animal glue as early as 1400 B.C. and actually literary references to glue manufactured from hides begin about 200 B.C.

In spite of the considerable variety of raw materials from which animal glues are prepared, they can be divided into two classes, hide glue and bone glue, this differentiation being made on the basis of source material rather than on the chemical characteristics of the finished product. Hide glues are made by the hydrolysis under mild conditions of the fibrous protein collagen which is usually regarded as the anhydride of gelatin.

The source of hide glue is the hide trimmings of animals as well as fleshings from the slaughterhouse. These protein-bearing materials are washed thoroughly and then swelled with lime solution after which the residual lime is washed out and neutralized. This clean stock is then extracted with hot water in a series of repeated extractions beginning at about 140°F. The successive extractions are carried out at increasingly higher temperatures, and each extraction continues for several hours. The last extraction is normally made at the boiling point. The first-run product is that of highest quality and is actually usually

set aside for use as a food gelatin and for uses such as photographic emulsions which require the highest purity. The water extracts obtained during the cooking operation are kept separate and are evaporated in vacuum evaporators to reduce the moisture content and leave heavy concentrated solutions. These are usually run into shallow pans where impurities and fat are skimmed off and the extract is decanted from the sediment. After clarification, decolorizing, and filtering, the glue solution is usually extruded onto a belt which forms an endless strip of glue jelly. This extrusion is cut into sections which are spread on the frames and further dried down until they reach a convenient moisture content. The large sheets of dry glue are then further ground or broken up into smaller pieces for packaging.

TABLE 2-1. GRADES OF ANIMAL GLUE

Adopted by the National Association of Glue Manufacturers

Grade	Jelly Strength (grams)	Viscosity (millipoises)
1	18	22
2	36	25
3	58	30
4	82	36
5	108	44
6	135	52
7	164	61
8	192	69
9	222	77
10	251	85
11	283	94
12	315	104
13	347	114
14	379	125
15	411	136
16	444	149
17	477	162
18	512	177

Bone glue, as the name implies, is derived from fresh green stock at the slaughterhouse and the bones from the renderer's operation. In general, the bones are cleaned, degreased, and decalcified, and then ground and cooked under pressure. Although the cooking temperatures are higher than for animal glue, the higher grades of bone glue may be of better quality than the lower runs of hide glue. The final

clarification and evaporation operations are similar to those employed with hide glue.

#### GRADES OF ANIMAL GLUE

Animal glues are graded according to viscosity and gelling strength. The grades generally recognized are shown in Table 2-1.

Hide glues provide the top grades, and usual commercial production is seldom below grade 7. The lower grade glues are either bone glue or blends of bone and hide glue.

The viscosities shown in Table 2-1 are the absolute viscosity in millipoises of a 12½ per cent concentration glue solution at 140°F, and the test requires that the soaking and melting of the glue be carried out under optimum conditions.<sup>15</sup>

#### PREPARATION OF ANIMAL GLUE

Animal glue is usually prepared for use by weighing out the proper amount of glue and cold water and allowing the mixture to soak for a period of time, depending on the physical degree of subdivision of the dry glue. The soaking period should not be sufficiently long to encourage bacterial growth, however, and is usually from 2 hr to overnight. When the glue has been completely swelled, the mixture is heated to a temperature which should not exceed 140°F. Excessive heat will result in degradation of the gelatin. Such hot animal-glue melts are used on stock to be glued which is usually maintained at temperatures of approximately 80°F, and the parts to be joined must be brought together while the hydrosol is still in a fluid state. As soon as the temperature falls below the "setting point," the joint is set and strengthened further by the gradual evaporation of the moisture from the hydrogel.

Some improvement in the water-resistance characteristics of animal glue can be obtained by adding oxalic acid and paraformaldehyde in proper ratio to the glue mix. Such a mixture has a working life of approximately 6 hr and develops its water resistance slowly over approximately 2 weeks. A typical formulation for this water-resistant glue would be as follows:

Dry animal glue	100	parts by weight
Cold water	225	parts by weight
Oxalic acid	5½	parts by weight
Paraformaldehyde	10	parts by weight

Films of animal glue are tough and flexible and may be rendered more so by plasticizing with glycerine or sugars of various kinds.

## ADVANTAGES AND LIMITATIONS

Animal glue because of the many grades can be adjusted to meet almost any adhesive requirement under service conditions for which it is suitable. Its durability under conditions where it is not subject to high humidity or variations in atmospheric conditions is excellent, and its strength in thick films is quite good. Joints made with animal glue have survived the test of time and endured many thousands of years. In spite of its lack of water resistance and currently high cost, animal glue is still the closest approach to an all-purpose adhesive, insofar as ease of use, gap-filling properties, and toughness or elasticity of the glue line are concerned. Its lack of moisture resistance and susceptibility to bacterial and fungus attack restrict the use of animal glue to indoor service in dry climates. Because of this limitation, animal glue's adhesive use is losing ground to the more durable synthetic adhesives.

## CASEIN GLUES

Casein, prepared from the milk of domestic animals, has long been known as an adhesive, but the industrial manufacture of casein glues in the United States began about 1900 with the formation of the Casein Company of America. Casein glues became commercially important in 1916-17 as water-resistant adhesives for aircraft construction during World War I.

Casein is one of the two chief proteins of milk and is prepared from skim milk by curdling with dilute acid at 95-100°F. The curd, crude casein, is washed, pressed, ground, and dried. The preparation of a satisfactory product depends on careful control of the curdling, freedom from fat, proper washing to remove the degraded protein and salts, as well as the complete thorough drying of the casein particles. Properly prepared raw casein should be capable of being completely peptized to form a hydrosol in weakly alkaline solutions. The water resistance of casein glues is achieved by forming the hydrosol of sodium or ammonium caseinate and mixing this with a dispersion of calcium hydroxide (lime), or other alkaline-earth metal salts. The calcium caseinate which is formed is only sparingly soluble in water and is the final film-forming bonding medium. These reactions take place at room temperature.

In practice, prepared casein glues consist of the dry mixture of casein, peptizing alkali or alkali salts, and lime. These commercial

preparations may also be mixtures of alkali caseinate and lime. They require only mixing with the proper amount of water to prepare the glue ready for use. In addition to the ingredients already mentioned, which are necessary for the chemical reactions of setting, prepared casein glues also usually contain foam depressants and preservatives to inhibit fungus and mold growths.

Casein glues are also marketed in emulsion form, and such emulsions will dry to form films which are water-resistant and do not re-emulsify on exposure to moisture.

A comprehensive survey of a large number of casein-adhesive formulations has been published by Browne and Brouse.<sup>16, 17</sup>

Casein adhesives are widely used in the manufacture of plywood and laminated timbers. In combination with sodium silicate,<sup>18</sup> they are used in the preparation of paper laminates, and they also find application in combination with soluble dried blood and rubber lattices<sup>19-21</sup> in the preparation of metal-to-wood adhesives.

A particular advantage of casein glues is their application possibilities at low temperatures since casein glues can be used at temperatures as low as 50°F, whereas most room-temperature-setting synthetic-resin adhesives require temperatures of approximately 70°F or higher for successful operation. The casein-glue system is alkaline, and therefore casein glues are suitable for the gluing of oily or resinous woods such as pine, teak, and yew as the presence of the alkali emulsifies the surface nonpolar film. The alkaline condition of casein glues is, however, detrimental in the gluing of certain wood species where the alkaline conditions have a tendency to stain or discolor acid woods and thin or light-colored veneers.

Since the solids concentration of casein glues is usually in the range of 33 per cent, some provision must be made for the redrying of casein bonded joints or for the release of solvent moisture.

In production operations,<sup>22, 23</sup> mixed casein glues are usually spread on mechanical spreaders of the metal-roller type, having corrugated rollers with either spiral or longitudinal corrugations of about 8 per in. (see Figs. 2-2 and 2-3). Spreading speeds are usually about 60 to 80 lin ft per min, and the spreading ratios are 60 to 75 lb of liquid glue mix per 1000 sq ft of single glue joints.

When properly protected against mold and fungus growth by the incorporation of preservatives, such as the chlorinated phenols, casein-bonded joints between wood surfaces are capable of high strength char-



acteristics and excellent aging properties if protected from high humidity atmospheres. In recent years, the use of casein for laminated constructions has been displaced to a considerable extent by the synthetic resin adhesives, particularly the resorcinol-formaldehyde combinations which are truly water-proof.

### VEGETABLE GLUES

Under the term vegetable glue are included those adhesives which are derived from natural gums and starches such as tapioca, potato, sago, waxy maize, corn, wheat, and similar starch-bearing roots, grains, and tubers. As adhesives for the production of laminates, we need only consider the starches used for the manufacture of plywood and paper laminates. The starches most widely used for such adhesives are principally tapioca and corn.

The advantages of starch adhesives<sup>22, 24-26</sup> are quick tack coupled with low cost, ease of preparation, and the fact that starch adhesives are odorless and nontoxic. Their chief disadvantage is lack of water resistance unless modified with formaldehyde or synthetic resins such as the urea formaldehydes.

Starch is usually considered to be made up of two types of carbohydrate molecules: amylose (20-40 per cent) and amylopectin (60-80 per cent). The amyloses are straight-chain molecules with a molecular weight varying between 10,000 and 60,000, whereas the amylopectin molecules are branch-chained and have molecular weights between approximately 50,000 and 1,000,000. In general, the amylose fraction of starch is considered to have little effect on the adhesive qualities of the starch glue. The amylose fraction is soluble in water, and once dissolved it begins to retrograde to glucose rather rapidly. Amylopectin, on the other hand, when heated with water forms a three-dimensional hydrogel. This gummy hydrogel is almost clear and odorless and does not paste back.

In commercial practice, native starch, which is the pure starch prepared from the grain or root, is seldom used for the preparation of glues as such, because glues made of raw starch do not give satisfactory bonds owing to their high water content at spreading consistency. The vegetable glue is supplied in dried form as starch which has been pretreated with acid or peroxides<sup>27-35</sup> or as a mixture of the raw starch and various additives which will reduce the viscosity of the final glue mix and allow a higher concentration of solids. Such materials are perborates or

peroxides or, in some isolated instances, enzyme concentrates. These prepared dry glues have infinite storage life. The usual procedure in preparing the pretreated or premixed glue for application is to heat together at about 160°F a slurry of 1 part of dry vegetable glue and 1¼ to 3 parts of water. The heating time is 15 to 30 min, and for the preparation of laminating glues sodium hydroxide ( $\text{Ca } \frac{3}{4}$  to 8 per cent on starch) is added to the cook. The addition of caustic improves the gumminess of the glue and also improves the penetration of the adhesive into the wood or paper to be bonded. There is some evidence for the existence of alkali starch comparable to alkali cellulose. Glue mixes prepared in this way have excellent stability and can usually be stored for several days without appreciable loss in adhesive properties.

The spreading of vegetable glues is carried out mechanically with corrugated roller spreaders. In the manufacture of plywood, the spreading rate is of the order of 15–25 lb of glue solids per 1000 sq ft of glue line.

Vegetable glues “set” by the evaporation of their water content or its diffusion from the glue line into the laminas, and therefore some redrying operation is often necessary for the finished laminate to return the assembly to its normal moisture content. Paper or fiberboard laminates are dried on the laminating machinery by means of the steam-heated rolls or “cans.” Plywood panels after clamping at room temperature for 1–16 hr may be redried to 6–8 per cent moisture in kilns or hot rooms with the panels separated on stickers to facilitate air circulation. The clamping time and necessity for redrying depend on the moisture content of the laminas before gluing and the water content of the vegetable glue mix as applied.

In recent years a development of the combination of starch adhesives with urea–formaldehyde resin <sup>36,37</sup> has made possible an improvement in the water resistance of the glue lines produced with starch adhesives. These combinations have been particularly successful in the manufacture of laminated fiberboard for use as shipping containers (V boxes). The urea–formaldehyde resin serves to block the free hydroxyl groups of the starch which are principally responsible for its water sensitivity. Usually 5 to 10 per cent of urea formaldehyde is used for this purpose. By the same token, the starch used should be as little degraded as possible, consistent with proper viscosity and handling characteristics.

The preparation of starch–urea–formaldehyde combinations can be carried out by gelatinizing the starch in the presence of the urea–formaldehyde resin or by adding a water-soluble resin to the starch

colloid after dispersion. The former method requires less urea formaldehyde to achieve comparable water resistance, and the stability of the adhesive is better than when the resin is added to the starch after cooking. The combination adhesive is catalyzed by adjusting the pH to 4.0-4.5 with aluminum sulfate or ammonium salts. Curing can be carried on at room temperature, but generally heat is used to accelerate the cure, particularly in paper-laminating operations.

### SOYABEAN GLUES

Soyabean glues are prepared from the protein content of the meal of soyabeans which is left after the extraction of the oil. In chemical characteristics, this vegetable protein is closely related to casein, although the viscosity of the undegraded protein molecule is considerably higher in aqueous dispersions.

The extracted soya protein is prepared for gluing in combination with alkalies and calcium hydroxide in a manner very similar to the handling of the casein. Several comprehensive reviews of soyabean proteins are available in the literature.<sup>38, 39</sup>

Soyabean glues for the manufacture of plywood were introduced in the Pacific Northwest in 1923 and achieved commercial importance about 1926. Their development has been due principally to the efforts of I. F. Laucks, who carried out the pioneering work with this adhesive. Soyabean glues are used principally for the bonding of interior-grade Douglas-fir and pine plywood although some low-grade industrial hardwood plywood and box-shook grades of hardwood are bonded with soyabean glues.

The soyabean glues may be either pressed at room temperature or used in combination with hot-pressing facilities. A typical soyabean-glue formulation is applied at 30 per cent solids in water at a spreading ratio of 60-70 lb of liquid mixture per 1000 sq ft of single glue line. In hot pressing, considerably lower spreads in the range of 40 lb of liquid mixture are generally used.

Soya protein glues have the advantage of low cost in combination with moisture-resistant characteristics similar to those of casein. They suffer from the drawbacks of high alkalinity, susceptibility to fungus and mold attack, as well as a tendency to stain through thin-face stock. Numerous combinations of soyabean glue with other adhesive materials such as blood albumen and synthetic-resin adhesives have been proposed, but they have not achieved commercial significance.

## BLOOD ALBUMEN

During the period 1916 to 1930, soluble blood albumen enjoyed a rather wide acceptance as an adhesive for the manufacture of plywood. The contribution of blood-albumen adhesives to laminating in the production of plywood is now, however, of almost purely historical importance, and the advent of synthetic resin adhesives in the same general price class has largely eliminated their use in commercial production.

The low-temperature evaporation of fresh cattle blood, either with or without the hemoglobin, at temperatures below approximately 140°F, either by spray drying or by evaporation in vacuum pans, resulted in an adhesive raw material which could be redispersed by peptizing for several hours in water and used in combination with ammonium hydroxide and calcium hydroxide as a plywood adhesive for moderate-temperature hot-press bonding.

Blood-albumen glues can be coagulated to a very water-resistant glue line at temperatures from 140° to 180°F. They are, however, very susceptible to fungus and bacterial attack and lose a considerable proportion of their strength on aging. The chief problems with blood-albumen adhesives are securing reproducible uniformity of the raw material without close manufacturing control and considerable difficulty in application in commercial production. In combination with other materials such as sodium silicate, urea-formaldehyde resins, and phenol-formaldehyde resins, they have provided extensively used adhesives for the bonding of plywood of moisture-resistant grades. Blood-albumen glues led to the installation of a considerable number of hot presses for plywood manufacture, and these encouraged developments in synthetic-resin adhesives. Blood glues continued in rather wide use in Europe, particularly Scandinavia, until as late as World War II.

SILICATE ADHESIVES <sup>25, 26, 40-42</sup>

Sodium silicate, so-called "water glass," manufactured by the fusion together of quartz sand and sodium carbonate in open-hearth furnaces at 1300-1500°C, is an excellent adhesive for applications such as corrugated fiberboard, solid fiberboard, or cheap grades of plywood. The solution of the reaction products of this fusion provides an adhesive which is strongly alkaline and sets by the absorption of its moisture by the material to be bonded. Sodium silicate solutions have little tack,

and bonds made with them are not particularly strong. Although lacking in water resistance, sodium silicate solutions are fire-resistant and free from attack by vermin, bacteria, or fungus.

#### MISCELLANEOUS ADHESIVES

In the production of paper composites for the packaging field, a considerable number of miscellaneous adhesives of various kinds have been used. These include natural gums and dextrans, rosin soaps, bituminous emulsions, and a variety of compositions which are applied as hot melts. The laminates produced with such adhesives are of specialized interest, however, and are seldom considered in structural-engineering design.

#### SYNTHETIC-RESIN ADHESIVES

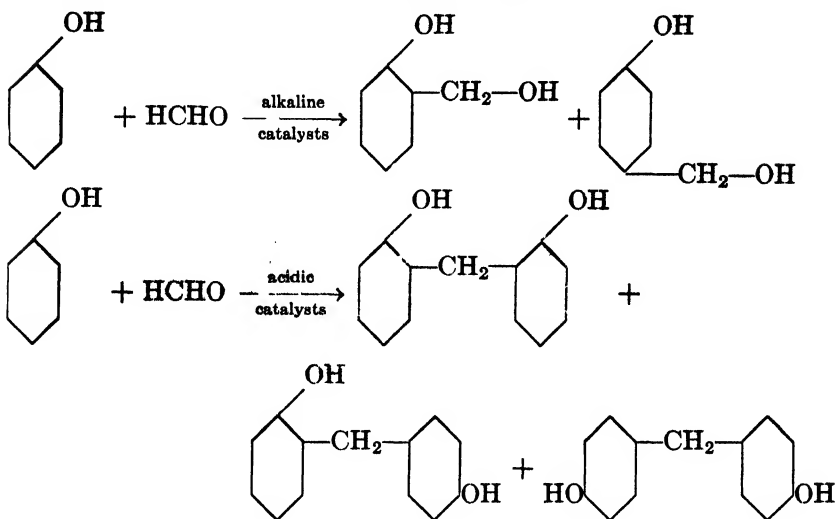
##### PHENOL-FORMALDEHYDE RESINS

The reactions of phenol and aldehydes was probably first recognized by Baeyer <sup>43</sup> in 1872. The commercial development of phenol-formaldehyde resins, however, did not begin until about 1909 when Baeke-land <sup>44</sup> discovered a technique for the molding of such materials. As early as 1912, the electrical industry began the fabrication of laminated sheets for insulating materials by combining phenol-formaldehyde-resin-impregnated paper and cloth under heat and pressure. The use of phenol-formaldehyde resins for the manufacture of plywood and wooden laminates occurred in the late 1920's and reached commercial importance with the manufacture of a phenolic-resin film adhesive <sup>45</sup> in the United States in 1934.

The final reaction product of most reactions involving phenols and formaldehyde are the phenol-formaldehyde resins. These fall into two distinctly separate groups: (1) fusible resins in which the component molecules have a linear chainlike structure and (2) insoluble infusible resins in which the component molecules are connected to form a three-dimensional cross-linked network. The type of finished resins obtained from a given condensation reaction is governed by the structure of the phenol and the nature of the reaction catalyst as well as the mole ratio of the formaldehyde to the phenol.

Although the final structure of phenol-formaldehyde-resin polymers is still the subject of some disagreement, the fundamental reactions between phenol and formaldehyde are fairly well established.<sup>46-48</sup> The two most important phenol-formaldehyde reactions are the formation

of the so-called phenol alcohols, nuclear methylol phenols, and the formation of polynuclear methylene derivatives.



A wide variety of catalysts is used for the condensation of phenol-formaldehyde resins, but the essential function of the catalyst is to provide either hydrogen ions or hydroxyl ions as the primary catalytic agents.

As shown in the previous equations, under alkaline condensation conditions, the formation of the so-called phenol alcohols or methylol derivatives is favored, whereas under acidic conditions the formation of methylene links between nuclei predominates.

The reactive positions on the phenol nucleus are ortho and para to the phenolic hydroxyl, and, therefore, it can be seen that, if sufficient formaldehyde is available, the formation of dimethylol and trimethylol phenols is possible under alkaline conditions. These phenol alcohols may react with each other by the elimination of water from a methylol group and a nuclear hydrogen of another phenol ring or by the elimination of formaldehyde and water between two methylol groups. The possibility of ether linkages produced by the elimination of water alone between two methylol groups has been the subject of some controversy. It appears probable that such ether linkages are followed by the release of one of the formaldehyde residues to produce a methylene link in the final polymer.

When the mole ratio of formaldehyde to phenol is less than one, fusible resins called Novolaks result from the formation of long chains

of methylene-connected phenol nuclei without cross linking. Such Novolaks are permanently fusible and can only be cured by the addition of methylene-producing materials such as formaldehyde, hexamethylene tetramine or paraformaldehyde.

For use as adhesives, the phenol-formaldehyde condensation is usually carried out under alkaline conditions and at a formaldehyde-to-phenol mole ratio above one. Under such conditions, a cross-linked resin molecule is built up which is capable of reaction to the final insoluble infusible state. The reaction is usually considered as passing through three stages. These stages are not particularly well defined but are still used to describe the approximate condition of a resin polymer. The *A* stage is essentially that of a mixture of phenol alcohols and resins of low polymer size which is fusible and solvent soluble. The *B*-stage resins are larger molecules, but the resin polymer is still fusible and sensitive but no longer soluble in solvents such as alcohols, ketones, and some hydrocarbons. The *C*-stage resin is highly cross-linked and in the final insoluble infusible form.

The phenol-formaldehyde resins used commercially as adhesives are usually in the *A* stage. They may be handled as solutions in water, alcohol, or other solvents, or as spray-dried powders or films carried on a lightweight tissue-paper base.

The formulation and curing properties of phenol-formaldehyde adhesives can be varied widely by variation in the proportions of formaldehyde to phenol, the composition and proportion of the curing catalyst, and the degree of polymerization of the resin before the final curing operation. Phenolic adhesives are usually formulated for a particular application, and it is therefore of the utmost importance to choose the phenol-formaldehyde resin on the basis of the materials to be bonded, the degree of flow required under the particular conditions of bonding, the curing speed required at the available temperature, and also for the properties desired in the finished construction. In general, commercial formulations are a compromise of the optimum desired properties since these characteristics are not independent.

For adhesive use, two general methods of preparation of phenol-formaldehyde resins are usually followed. The first, which is used for the preparation of laminating varnishes, involves the production of an alkaline condensed phenol-formaldehyde polymer in aqueous solution. When the condensation has proceeded to the desired point, the alkaline

catalyst is neutralized, and phase separation between the resin and the water takes place. The aqueous layer is removed, and the resin is dehydrated, usually under vacuum, and then dissolved in alcohol or other solvents. This solvent solution is then used for the impregnation of cloth or paper, the saturated laminas are dried to the desired state and then assembled for pressing and final cure under heat. The second general scheme, generally used in the preparation of phenolic adhesives for wood or for the production of laminates without simultaneous impregnation, involves the production of the alkaline-condensed phenol-formaldehyde resin in aqueous medium. This aqueous solution is then applied to the surfaces to be bonded as such, or spray-dried to produce a powdered form which is readily resolvable in water or alcoholic solvents or coated and impregnated on a lightweight tissue carrier and dried for the production of the adhesive in film form.

The principal virtue of the first method outlined is the elimination of the condensation catalyst which may influence adversely the properties of the finished laminate. This factor is particularly important when paper-base or cloth-base laminates are to be used for electrical purposes. The latter preparation method has the advantage of simplicity and lower cost. Since the condensation catalyst remains present during the final curing operation, these latter preparations are also faster-curing at lower curing temperatures and also have considerably less flow during the curing operations than the first type described.

The cure of alkaline-condensed phenolic resins which have been neutralized and dissolved in solvent can be greatly accelerated by the use of acids. This catalytic system has not been particularly popular for the preparation of structural laminates because of the possibility of the deleterious effect of the rather high acidity required for curing on the materials to be bonded. This effect is particularly serious in the lamination of wooden structures.

Phenolic adhesives are applied from water or other solvent solutions by spreading on the surfaces to be joined. In general, sufficient time is allowed to elapse between spreading and pressing, either in open or closed assembly, for the solvent to evaporate or penetrate the materials to be laminated if these should be sufficiently porous. Unless a substantial proportion of the solvent is allowed to evaporate, the possibility of steam blisters between the laminas and excessive flow of the adhesive is probable. In certain well-organized operations, such as



the manufacture of Douglas-fir plywood, this necessary assembly time is reduced to a minimum by adjustments in formulation and by drying the individual veneers to very low moisture content in order that the solvent water is rapidly absorbed from the glue line.

Although some phenol-formaldehyde adhesives can be cured at room temperature, most commercial phenolic adhesives are used in combination with hot-pressing equipment. The temperatures employed for bonding with phenol-formaldehyde resins range from 240° to 325°F, depending on the formulation of the resin and the pressing time desired. Laminating pressures vary widely from the approximately 150–175 psi used in the manufacture of softwood plywood to pressures of the order of 1000–1500 psi used in the manufacture of cloth-base or paper-base laminates and high-density woods such as Compregwood.

The low-temperature bonding of phenol-formaldehyde resins can be carried out from room temperature to the conditions available in heated kilns. The use of unmodified phenolics for such bonding operations usually depends on strongly acidic curing conditions. The low-temperature cure of alkaline condensed phenolic adhesives can be accomplished by the use of proportions of more reactive phenolic resins such as resorcinol-formaldehyde combinations (see below).

Phenol-formaldehyde adhesives are frequently used in conjunction with other materials. Small proportions of inert cellulosic materials may be used as flow-control agents in order to retain the resin insofar as possible in the glue line during the curing of the resin and to reduce the flow tendency of the adhesive. In addition to these materials, however, extenders of various kinds may be used in order to reduce the glue-line cost. Phenol-formaldehyde resins have been used in combination with other adhesives and synthetic polymers as well as with flour, blood albumen, soyabean meal, corn gluten, lignin, and numerous other low-cost materials which are often adhesives in their own right. In most cases, the incorporation of extenders of the kind previously mentioned results in a reduction of the durability of the glue line as well as of the curing speed of the phenolic resin.

The wide acceptance and use of phenol-formaldehyde resins, not only as adhesives but also for molding compounds and coating materials, results from the outstanding properties of these resins in their final cured state. When properly applied and cured, phenol-formaldehyde resins are outstanding in their durability characteristics.

Phenolic glue lines show practically no deterioration on aging, and, in addition, they are resistant to almost all chemical agents with the exception of strong alkalis. Phenolic glue lines are truly waterproof and are virtually unaffected even by boiling water. Their durability over a wide range of service conditions is superior to almost all adhesive materials of either natural or synthetic origin. Phenol-formaldehyde adhesives are not attacked by bacteria or fungi and will withstand elevated temperatures with undiminished strength under high humidity conditions. Phenol-formaldehyde adhesives for wood have been the standard of durability against which other adhesive materials are compared.

#### RESORCINOL-FORMALDEHYDE ADHESIVES

Resorcinol, metadihydroxy benzene, belongs to the generic class of phenols and its reactions follow the general pattern with formaldehyde which has been outlined for simple phenol. The presence of the second hydroxyl group, however, increases greatly the reactivity of the nuclear hydrogen atoms. The number of formaldehyde reactive positions in the benzene nucleus of resorcinol is the same as for simple phenol, however.

The resin-forming potential of resorcinol in combination with aldehydes has long been recognized,<sup>49</sup> but the commercial preparation of these resins from resorcinol and formaldehyde did not begin until 1943. Their introduction was the result of the demand during World War II for an assembly adhesive for the gluing of wooden aircraft and marine structures which would be entirely waterproof and which could be cured at room temperature.

Because of the high reactivity of resorcinol, it is not possible to form resorcinol-formaldehyde resins which are stable at ordinary temperatures unless the formaldehyde-to-resorcinol mole ratio is less than one. Under mild catalytic conditions and in the presence of a solvent, it is possible, however, to control the reaction and form stable Novolak resins.<sup>50-52</sup> For use as adhesives, such Novolak solutions are further reacted with methylene-producing "catalysts" consisting usually of paraformaldehyde or aqueous formaldehyde and a small proportion of filler, such as walnut-shell flour. In the presence of the additional formaldehyde, polymerization can continue at ordinary temperatures until the final C-stage polymer is reached.

The commercially available resorcinol-base adhesives may be formulated entirely on resorcinol as the phenolic constituent or as mixtures of resorcinol and simple phenol-formaldehyde resins. These combinations are usually furnished as a solution of 55–70 per cent resin solids in water or water-alcohol mixtures. For use, the stable resin solution is then mixed with 15–20 per cent of “catalyst.” In the presence of the additional formaldehyde, the pot life before gelation is usually of the order of 3 hr at 75°F.

For gluing at ordinary temperatures, the maximum permissible assembly time with resorcinol-formaldehyde adhesives is understandably short. Where the cure of the adhesive is to be accelerated by heating of the joint, the permissible assembly time is somewhat longer. In general, for room-temperature work, the assembly should be brought under pressure in 20–60 min, and, for hot pressing, the maximum assembly time is still of the order of 120 min.

The rate of cure of resorcinol adhesives can be considerably accelerated by the use of moderate heat, and, therefore, these resins are particularly adapted to the use of high-frequency heating or the heating of large laminated timbers in kilns.

Joints bonded with resorcinol-formaldehyde adhesives should be cured at temperatures above 75°F, although a considerable portion of the joint strength can be achieved at lower temperatures. A recent bulletin<sup>28</sup> by the Forest Products Laboratory at Madison, Wis., provides a review of the strength in wooden assemblies which can be achieved under low-temperature bonding conditions with two typical resorcinol adhesives.

Joints made in wooden structures with resorcinol adhesives achieve their *maximum* strength and permanence at curing temperatures above 140°F, and such curing conditions are recommended for structures which are subject to high glue-line stresses or where the utmost in durability is required. Typical of such constructions are laminated keels and marine timbers which are used under alternating wet and dry service conditions.

Although resorcinol adhesives were developed primarily for wooden structures, excellent joints can be obtained on phenolic laminates, rubbers which have been cyclized, and on thermoplastic materials such as the acrylic resins.

The durability of resorcinol-formaldehyde joints is comparable with that of hot-press cured phenol-formaldehyde resins, and, therefore, the use of resorcinol adhesives is becoming widespread in the assembly of structures which are exposed to the severest weathering conditions.

They are particularly adapted to the lamination of timbers and keels as well as for prefabricated housing structures and for the assembly gluing of wooden boats and wooden aircraft.

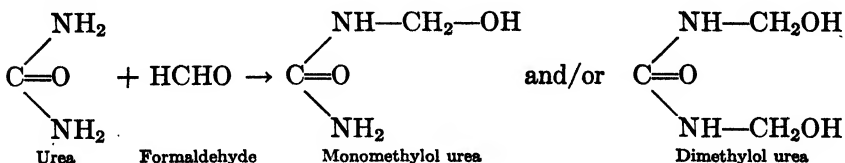
#### OTHER PHENOLIC ADHESIVES

As might be expected from the basic nature of the reaction, many other phenolic bodies and aldehydes have been investigated for the production of phenolic adhesives. For laminating purposes, however, the only commercially important adhesives have been based on combinations of formaldehyde with cresol mixtures which are high in meta-cresol content and on the reaction of phenol with furfuraldehyde (see below).

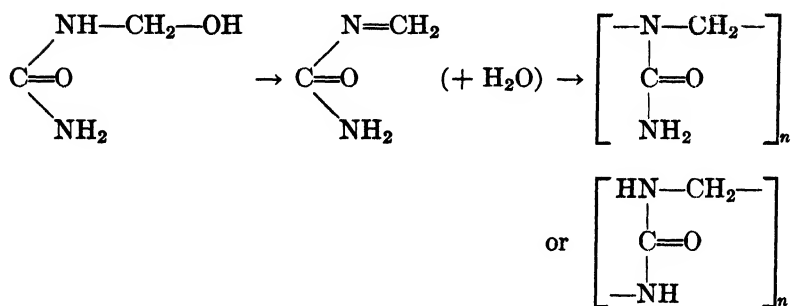
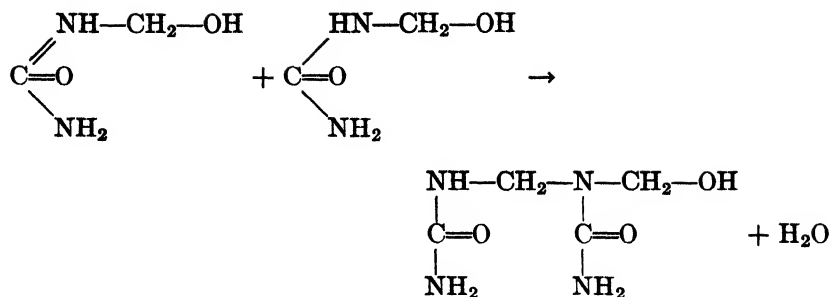
#### UREA-FORMALDEHYDE RESINS

Although the possibility of using resins produced by the condensation polymerization of urea and formaldehyde was pointed out by John in 1920, it was not until 1935 when the production of cheap synthetic urea was begun in the United States that the urea-formaldehyde adhesives achieved commercial importance. Hot-pressing facilities installed during this period for the use of Tego film provided further stimulus for these adhesive developments. Since that time, the use of urea-formaldehyde adhesives has grown rapidly, particularly for the manufacture of plywood so that today, the "ureas" are the most widely used adhesives in this field.

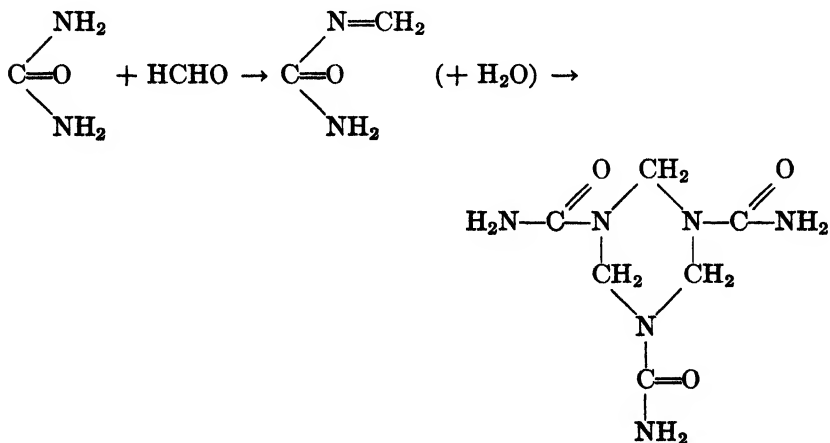
The reaction of urea and formaldehyde under neutral or slightly alkaline conditions results in the first instance in the formation of the monomeric monomethylol and dimethylol ureas, depending on the ratio of formaldehyde to urea.



Further reaction for polymer formation may occur by several proposed mechanisms, all of which involve condensation with the elimination of water between the methylol groups and hydrogen bound to one of the nitrogen atoms. This may occur either directly or through the intermediate formation of a methylene imine. These mechanisms<sup>53</sup> are illustrated by the following equations:

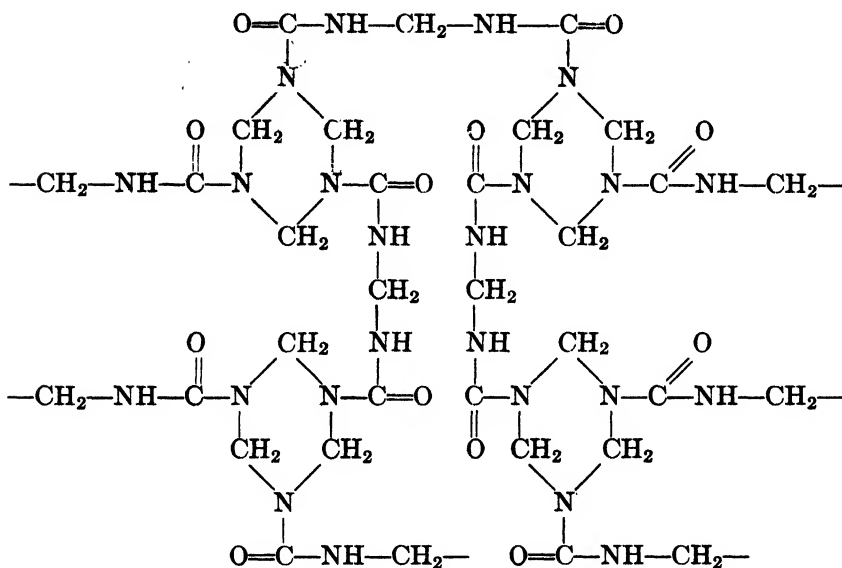


Thurston <sup>54, 55</sup> has suggested that the building unit of urea-formaldehyde polymers is a cyclic trimer formed when both  $-\text{NH}_2$  groups of the urea react with formaldehyde and then go through the methylene imine stage according to the following reaction:



Such trimers would serve as the polymer units.

Marvel<sup>56</sup> and his coworkers have recently extended this approach and proposed that urea reacts with formaldehyde as an amino acid amide. In such a molecule, the amide  $\text{NH}_2$  would react with formaldehyde to yield methylene bis amide links between cyclic trimethylene-triamine rings formed by the reaction of the amine  $\text{NH}_2$  with formaldehyde. The resulting final polymer would be a highly cross-linked structure such as shown below.



Although there is still insufficient evidence for a complete picture of the fine structure of the fully polymerized urea-formaldehyde resin, it is generally agreed that the aqueous condensation products most widely used as adhesives consist of essentially linear polymers of 10–20 urea units. The conversion to the final infusible stage is the result of very frequent cross links between chains to form a complex three-dimensional network.

The preparation of urea-formaldehyde adhesive resins is usually carried on at formaldehyde-to-urea mole ratios between 1.5 and 2.0 and at a  $\text{pH}$  level between 4 and 8 in aqueous medium. If the reaction, which is very sensitive to  $\text{pH}$ , is carried on under proper conditions, the polymer is hydrophilic, and no precipitation of undesirable by-products occurs during condensation. The condensation temperatures are approximately 60–100°C. When the resin formation has reached

the proper point, the aqueous solution is dehydrated by distillation under vacuum to concentrate the solution, or the reaction mixture is spray-dried to provide a stable water-dispersible powder. In spray-drying operations, a small proportion of cellulosic filler such as walnut-shell flour is often added to the condensate in order to control the particle size during the spray-drying operation.

The cure of urea-formaldehyde adhesives to the final infusible state occurs very readily in the presence of acids. Thus, bonding may be carried out at ordinary temperatures as well as at elevated temperatures by adjusting the  $pH$  of the glue mixture. The adjustment of  $pH$  for the cure of urea-formaldehyde resins is seldom carried out by the direct addition of acid. More frequently, the catalysts employed are ammonium salts of various organic and inorganic acids. The ammonium ions react slowly with the available formaldehyde in the adhesive formulation to form hexamethylene tetramine with the gradual liberation of the free acid. Since the urea-formaldehyde resins may be subject to degradation and a loss of cohesive strength when condensed under excessively acidic conditions, the choice of catalysts requires considerable discretion. Excessively acidic conditions at the glue line also may have a deleterious effect on the materials being bonded,<sup>57</sup> and a minimum  $pH$  for the cured glue line has been included in several Government specifications for room-temperature-setting urea-formaldehyde adhesives (see page 163).

In room-temperature bonding operations, urea-formaldehyde glue lines usually require operating temperatures of 70°F or above. At these temperatures, the normal bonding time under pressure is several hours, and the glue line does not reach its maximum shear strength and water resistance for several days.

For elevated temperature bonding in hot presses, the platen temperature is usually maintained at 240–270°F. Actual glue-line temperatures are of the order of 230°F at the time pressure is released. Under such conditions, the curing time of commercial urea-formaldehyde adhesives is a few minutes.

Urea-formaldehyde glues are usually applied to the surfaces to be bonded at solids concentrations between 50 and 70 per cent solids. The low proportion of water introduced into the laminate under these conditions eliminates the necessity for redrying the assembly after gluing. Urea glues are usually applied by mechanical spreading with corrugated-rubber roll spreaders. Glue spreads with synthetic-resin adhesives are usually considerably lower than with other types and a

spread of 30-35 lb of liquid glue per 1000 sq ft of single glue line is adequate for hot pressing if the surfaces are smooth and well fitted. Higher spreads are required in cold pressing, usually 40-60 lb on the same basis. Spreading speeds are of the order of 60-80 lin ft per minute.

Urea-formaldehyde glues are seldom used without modification or extension. In practice, by far the most common extender for urea-formaldehyde glue formulations is wheat flour. A small proportion of such extenders, of the order of 10-20 per cent of extender, based on urea-formaldehyde solid, has little effect on the strength or durability of the glue line. Extender ratios as high as 250 per cent of wheat flour are in common use for the production of lower grades of plywood. The durability of the glue line is progressively reduced as the extender ratio increases. Thus, it is possible to formulate glues over the complete range of quality and cost, from formulations which have the maximum durability and water resistance that can be achieved with unmodified urea-formaldehyde resins, to formulations which are competitive in cost but still superior in durability to vegetable glue and soyabean glue formulations.

Because of their lack of gap-filling properties and their tendency to craze in thick glue lines which have been cured too rapidly, urea-formaldehyde adhesives are often modified with materials which will improve the strength of the adhesive film in thick sections and achieve better gap-filling properties. The materials most frequently incorporated for this purpose are benzyl alcohol, furfuraldehyde derivatives, and fillers such as finely ground C-stage phenol-formaldehyde resin. With the exception of the last expedient, which was used extensively in Germany under the designation "Klemmleim," the incorporation of such gap-filling additives in commercial urea-formaldehyde adhesives has usually resulted in a product of limited storage stability and higher cost.

Other additives for use with urea-formaldehyde resins have had as their objective the improvement of the durability of the cured resin adhesive film. Such fortification of the urea-formaldehyde glue line is possible with the use of resorcinol, melamine, or melamine resins. The incorporation of as little as 5 per cent of resorcinol on urea-formaldehyde solids will produce a glue line which, when properly cured, will stand the effects of boiling water. Except in specialized cases, the fortification of urea-formaldehyde resins is not justified on a cost basis, since the formulations are not competitive costwise with phenol-form-



aldehyde bonds, and the durability achieved is not equal to that possible with the phenol formaldehydes.

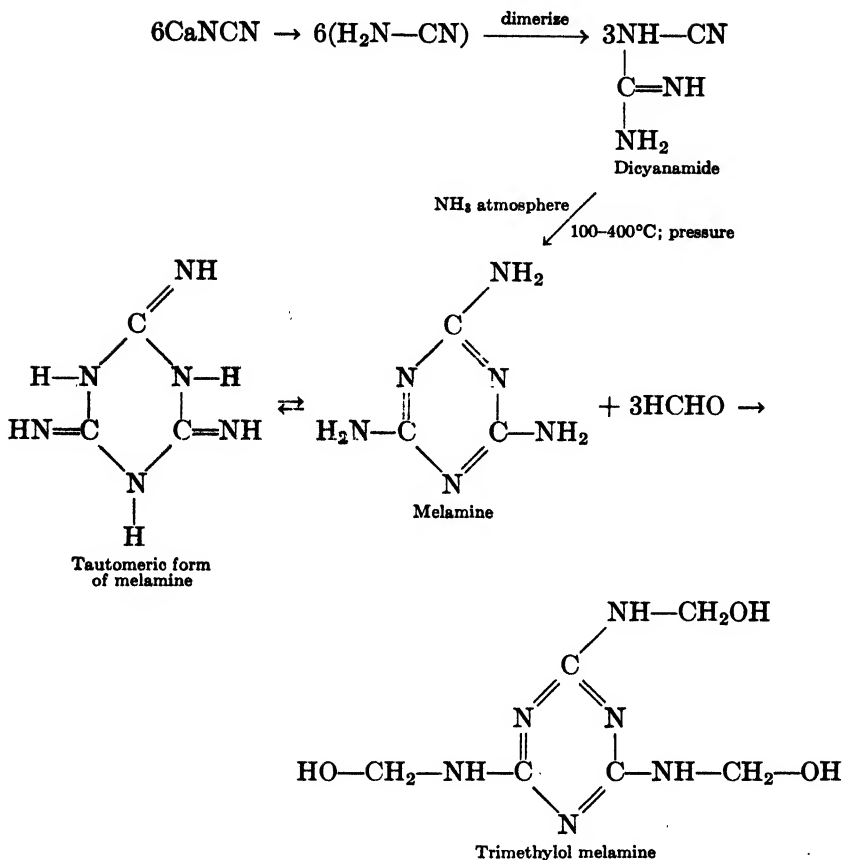
The durability of urea-formaldehyde glue lines has been the subject of considerable investigation.<sup>58</sup> Such glue lines are characterized by high shear strengths and excellent water resistance. It is erroneous, however, to characterize urea-formaldehyde glue lines as waterproof. Properly cured urea-formaldehyde bonds will withstand prolonged soaking in water at room temperature without serious loss of strength. Their recovery of full strength on redrying is excellent, but repeated soaking and drying cycles will eventually lead to glue-line failure. At elevated temperatures, urea-formaldehyde bonds become moisture-sensitive, and such bonds will lose their strength rapidly when soaked at water temperatures above approximately 150°F. The approximate values to be expected from various shear-strength tests are outlined under standards and specifications (see page 163).

Although urea-formaldehyde bonds have excellent strength and good aging characteristics, they should be used with discretion where service conditions of high temperature or high humidity are to be encountered. Unprotected, the urea-formaldehyde glue lines are not suitable for outdoor exposure. When properly protected, however, their service record in all but heavily stressed constructions has been excellent.

The use of urea-formaldehyde resins in largest volume has been in the manufacture of plywood. Such plywood panels have been varied in quality from the low grades used in the furniture industry as drawer bottoms and dust backs to the type panels furnished under lend-lease specifications<sup>59</sup> for the construction of temporary housing in Great Britain. In general, urea-formaldehyde adhesives form excellent bonds with strongly polar and hydroxyl bearing surfaces such as wood and paper. These resins have been used for the bonding of such diverse materials as melamine-formaldehyde laminates and asbestos board to wood. They are not useful for the bonding of metals or nonpolar plastic surfaces.

#### MELAMINE-FORMALDEHYDE RESINS

Melamine-formaldehyde resins are formed by the reaction between melamine, more precisely named 2,4,6-triamino-1,3,5-triazine, and formaldehyde in neutral or slightly alkaline medium. The synthesis of melamine<sup>60,61</sup> from calcium cyanamide and its subsequent reaction with formaldehyde to form trimethylol melamine is illustrated by the following reactions:



Melamine is capable of reacting with 1 to 6 moles of formaldehyde to yield all the possible methylol derivatives. The monomeric methylol melamines are clear water-white and water-soluble products which can be isolated as hydrates with definite chemical characteristics.

The general chemistry of melamine-formaldehyde reactions follows the pattern previously outlined under urea-formaldehyde resins, except that melamine exhibits a greater functionality toward formaldehyde than does urea. Resin formation from the methylol melamine derivatives is generally considered to take place by the condensation of the hydroxyl of methylol groups with amino hydrogen to eliminate water and form methylene bridges. There is some evidence, however, for the formation of methylene ether links by the elimination of water between two methylol groups. In final cured form the resin polymer is a highly cross-linked three-dimensional network.

Melamine-formaldehyde resins are very resistant to hydrolysis and exhibit heat stability superior to those of urea formaldehyde. The high functionality of melamine toward formaldehyde is responsible for the rapid cure, hardness, and pronounced brittleness of the final form of these resins. Properly cured adhesive films are clear or colorless and exhibit outstanding chemical resistance and heat stability.

The reaction of melamine and formaldehyde during resin formation is very sensitive to hydrogen-ion concentration, and aqueous solutions of the resins suitable for adhesive purposes present problems of storage stability. For this reason, the melamine-formaldehyde resins offered commercially are usually in spray-dried form as powders which are re-dispersed in water or water-alcohol mixtures for application to the surfaces to be bonded.

Melamine-formaldehyde adhesive resins may be cured at temperatures from kiln temperature to moderate hot-press temperatures of approximately 240°F by the adjustment of pH with acidic or acid-forming catalysts. The general handling characteristics of melamine-formaldehyde adhesive resins are similar to those employed with the urea formaldehydes. The fully cured adhesive films, however, exhibit durability characteristics quite close to those of phenol-formaldehyde resins rather than those of the ureas. Glue lines of melamine resins will withstand prolonged immersion in boiling water, and the durability of kiln-temperature-cured melamine-formaldehyde joints approaches that of the resorcinols.

Because of their currently high cost, melamine-formaldehyde adhesive resins are very frequently used as fortifying agents for the less expensive urea formaldehyde with which they are compatible. Such combinations<sup>42</sup> have considerably improved water resistance with proportions of melamine-based resin of 10-15 per cent.

The chief application for melamine resins has been in the preparation of laminates in which the resin is the impregnating and surfacing material in addition to acting as the adhesive for joining the laminate. The transparency of the cured surface film is particularly advantageous in decorative laminates in which the pattern is often printed on the paper layer which forms the outside ply. Such constructions are familiar as table and counter tops. The electrical properties and heat resistance of such laminates are outstanding, and these properties are the basis of many of the industrial applications of melamine laminates.

#### POLYVINYL RESINS

The use of polyvinyl resins for the production of engineering laminates has been restricted to a few members of this general classification.

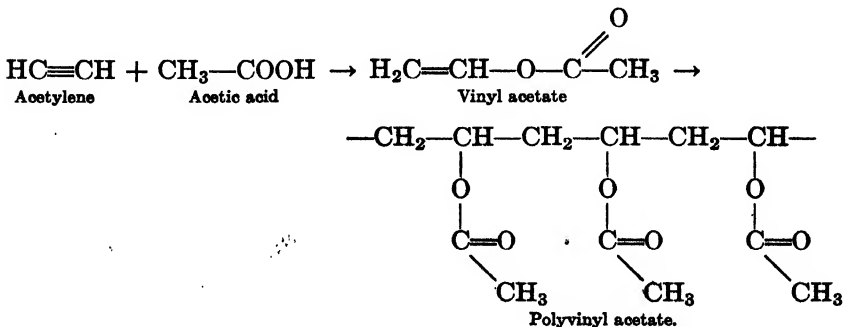
Since rapid strides are being made in this field, however, particularly in the use of polyvinyl resins in combination with other materials, a brief review of this group is probably desirable.

#### POLYVINYL ACETATE

Vinyl acetate was first described by Klatte<sup>63</sup> who prepared it by passing acetylene through acetic acid in the presence of a mercuric sulphate catalyst. The production of the present-day vinyl acetate is still from these raw materials, although a variety of other catalysts is employed. The stabilized vinyl acetate monomer has a boiling point of approximately 72°C and is available commercially with a purity of over 99.5 per cent. Polymerization is usually inhibited by the addition of a copper salt which may be removed by distillation.

The polymerization of vinyl acetate is usually carried on either in the presence of a solvent or by "emulsion polymerization" during which the vinyl acetate is the discontinuous phase. Peroxide catalysts are usually employed. The polymer size is determined not only by the rate of polymerization, the catalyst, and its concentration, but also by the particular solvent medium. The extensive use of polyvinyl acetate has been limited by its inability to form high polymers; the average molecular weight of commercial polyvinyl acetate resins is between 5000 and 20,000, although under particularly mild conditions it is possible to obtain polymers with a molecular weight of 80,000. The importance of vinyl acetate resins arises from their use as starting materials for other resins and as components in compositions in which vinyl acetate is copolymerized with other vinyl types.

The polymerization of vinyl acetate is linear, and it is generally agreed that the polymerization takes place "head to tail." The sequence of reactions is:



Polyvinyl acetate is thermoplastic, and the softening point depends on the polymer size but, in general, for commercially available resins,

varies between 50° and 90°C. The films of polyvinyl acetate are colorless, odorless, and nontoxic. They are water-sensitive, particularly if laid down from emulsions, and are soluble in a variety of solvents. Although resistant to weak solutions of acid or alkali, the resin is hydrolyzed by both strong alkalis and acids, particularly at higher temperatures.

Solutions of polyvinyl acetate as adhesives are characterized by high initial tack and excellent specific adhesion to a wide variety of materials. The high solvent content of such cements has limited their use on impervious surfaces over large areas where the removal of solvent is slow. Emulsions of polyvinyl acetate are offered commercially as adhesives for wood and other cellulosic materials.

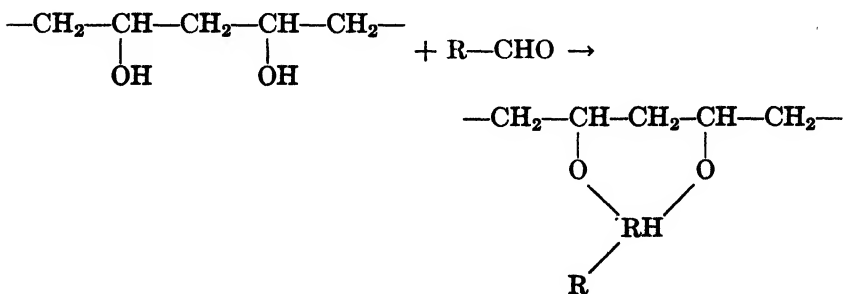
### Polyvinyl Alcohol

Monomeric vinyl alcohol has never been prepared, and the polyvinyl alcohol is usually obtained by the hydrolysis under either acid or alkaline conditions of polyvinyl acetate.<sup>64</sup> As may be seen, a wide variety of polymers is possible, depending on the size of the parent polyvinyl acetate as well as the degree of acetate group removal. The water solubility of polyvinyl alcohol depends on the residual number of acetate groups, and it may vary from grades which are only water-sensitive and still soluble in organic solvents to resins containing up to 40 per cent of polyvinyl alcohol units which are completely soluble in cold water.

The principle use of a polyvinyl alcohol as an adhesive for laminating has been in combination with starch for the production of weatherproof fiberboard (V boxes).

### Acetals of Polyvinyl Alcohol

When polyvinyl alcohol is condensed with aldehydes in the presence of an acid catalyst, cyclic acetals are formed.



The two commercially important acetals of polyvinyl alcohol result from the condensation with formaldehyde and butyraldehyde and are designated, respectively, as polyvinyl formal and polyvinyl butyral. Here again, a wide variety of resins of varying gradation are possible, depending on the number of residual acetate groups present in the polyvinyl alcohol and the extent of acetal formation.

The principle use of the acetals of polyvinyl alcohol as laminating adhesives has been in the manufacture of laminated safety glass. A plasticized polyvinyl butyral has been the principle adhesive used for this purpose in recent years. Although both polyvinyl formal and polyvinyl butyral have been used for the bonding of wooden structures and laminates of densified wood, their use has been limited by their thermoplastic properties and cost. In combination with phenol-formaldehyde resins to reduce their solubility and thermoplasticity, polyvinyl acetals have been used as laminating varnishes.<sup>65</sup>

### Polyvinyl Chloride

Although polyvinyl chloride and copolymers of vinyl chloride and acetate have been widely used as coating materials for cloth and as free films, such polymers have not achieved any wide distribution for adhesive applications. Their properties do not appear to be well suited to laminating, and, except in specialty adhesives, their use is limited.

### Acrylic Resins

The polymers of acrylic and methacrylic esters are familiar as brilliantly clear sheets and fabricated articles such as aircraft enclosures and injection moldings. These resins may be polymerized in organic solvent solutions or as emulsions to form useful cements. The polymers that are formed in organic-solvent media are characterized by excellent adhesion to metal, glass, and other impervious surfaces, as well as to porous materials. Acrylic films, although thermoplastic and solvent-sensitive, have excellent color retention and durability. Their relatively high cost has been the principal barrier to more widespread application in the adhesive field.

### CONTACT-LAMINATING RESINS <sup>66,67</sup>

During World War II, a new type of composition known by a variety of names—"low-pressure laminating resins," "contact resins," "impression resins," and so on—came into existence. These compositions were first developed as an attempt at a new form of polymerized cast sheet for aircraft glazing. Their volume war use, however, was in the form

of glass cloth laminates which served as lightweight armor (Doron) and for structural purposes in aircraft manufacture. Development work is proceeding rapidly in this field at the present time and these compositions are being used in casting, molding, impregnating, and other fields in which thermosetting materials can be applied. We need concern ourselves here only with their use as adhesives in the manufacture of laminates.

The contact resins fall into three general types; (a) an unsaturated high-molecular-weight monomer (often an allyl ester), (b) a mixture of an unsaturated polyester or alkyd in a solution of styrene and/or other monomer, or (c) some combination of (a) and (b). Regardless of composition, each is handled in much the same way; that is, a catalyst is added to the fluid composition; the catalyzed mixture is applied to the base material, and the construction is cured by heat and, as a rule, under very low pressure. Curing speed, inhibition of the cure by air, as well as flammability, rigidity, cost, and other characteristics of the cured polymer or copolymer, are dependent on the type of monomer and the type of unsaturated ester. The final form of these resins may be rigid masses, similar to molded or laminated phenolic compositions, or they may be extremely flexible compositions. Their polymerization behavior is similar to that of other vinyl types in that the resins are 100 per cent reactive and cure by polymerization or copolymerization rather than by condensation, and no volatile by-products are split out during the reaction.

Until 1948, most contact resins have been based on either the styrene or diallyl phthalate systems combined with suitable modifying polyesters or alkyds. It is obvious that with a choice of vinyl monomer and a wide variety of types and proportions of polyester, an almost infinite gradation of properties is possible in the contact-laminating field. The commercially available materials range from those which cure to quite flexible form to those which are of extremely hard and rigid compositions. Industrial research for the production of new compositions, as well as the exploration of the possible uses of these resins, is proceeding at a rapid rate, and, although predictions in the field of synthetic resins are hazardous, it seems likely that this generic class of compounds will find extensive use in many fields over the coming years.

Excellent rigid thermoset contact resin laminates, based on glass, fabric, or paper, have already appeared commercially. Laminates with some degree of flexibility have also been produced, but, of course, in multi-ply constructions the inherent rigidity of the laminate masks the flexibility of the adhesive resin. The contact resins have some very de-

sirable properties in comparison with the conventional phenol- or urea-formaldehyde and melamine-formaldehyde materials. Their color is usually better than the lower-cost phenolic laminates, and their water resistance and flexibility are considerably better than the ureas. In addition, they do not require the rather expensive treating equipment and high-pressure hot presses which are used with the older laminating materials.

Low-pressure laminating techniques \* seem to follow two general types: (a) continuous laminating and (b) producing individual laminated constructions. The technique of continuous laminating is based on equipment which will impregnate, combine and cure flexible or rigid laminated sheet stock. The design and construction of these units is not standardized, and the type of heating, speed of conveyor, width of sheet, and other factors will vary from unit to unit. Most operations, however, are based on the use of cellophane or coated paper under some tension to support and confine the laminated construction during the cure. There is little published information available on this technique, but a large volume of excellent laminated materials has been and is being produced by this method. This technique also has the advantage over other laminating processes of enabling the production of pieces of very large area.

TABLE 2-2. PHYSICAL PROPERTIES OF GLASS CLOTH LAMINATE BASED ON CONTACT RESIN

Property	Value
Specific gravity	1.87
Per cent weight Resin *	34.0
Per cent volume glass	51.3
Per cent water absorption	0.23
Impact-edge unnotched	16.6
Tension	45,380 psi
Modulus of elasticity in tension	$2.68 \times 10^6$ psi
Flexure	77,850 psi
Modulus of elasticity in flexure	$4.34 \times 10^6$ psi
Compression	34,300 psi

\* Paraplex P-43, Resinous Products and Chemical Co., Philadelphia, Pa.

The structural and strength characteristics of laminates made from the contact resins will vary considerably, depending on the base material as well as on the composition of the laminating resin. For reference purposes, however, the physical characteristics of two typical laminates are given in Tables 2-2 and 2-3.

\* See also Chapters 6 and 22 for discussions of laminating techniques.



TABLE 2-3. PHYSICAL PROPERTIES OF 8-OZ ARMY COTTON-DUCK 15-PLY LAMINATES TREATED WITH CONTACT RESIN

Composition and Properties	Laminate 130	Laminate 132
Composition		
Cotton duck	45.5%	40.4%
Contact resin *	54.5%	55.6%
Urea-formaldehyde resin †	.....	4.0%
Final thickness (inches)	0.292	0.322
Density	1.32	1.33
Water resistance *		
Gain in weight	1.11%	0.85%
Solubles	-0.06%	-0.02%
Total gain	1.11%	0.85%
Rockwell hardness, M scale	84	90
Flexural tests, ultimate strength (psi)	15,300	12,700
Modulus of elasticity in bending, $E_B$ (psi)	872,000	867,000
Edge compression, ultimate strength (psi)	20,900	19,900

\* Both specimens showed about 0.3 per cent swelling perpendicular to the laminations during soaking and 100 per cent recovery on redrying.

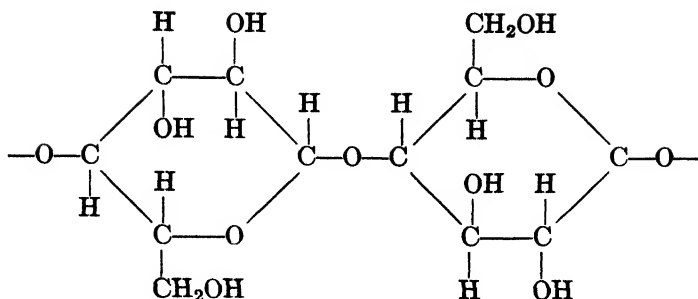
† Uformite 609, Resinous Products and Chemical Co., Philadelphia, Pa.

### ALKYD CEMENTS

Although modifications of glyceryl phthalate with vegetable or fish oils are widely used as materials for protective coatings, they are not particularly useful as adhesives. As components of laminates, however, they are occasionally encountered as sizing materials, particularly for metals. Alkyds may be formulated for excellent specific adhesion to metal surfaces, and such primed or sized metal laminas after drying may be bonded into composite structures with adhesives which have poor adhesion to metal and yet produce excellent bonds between the alkyd coating and the other laminate members.

### CELLULOSE DERIVATIVES<sup>68, 69</sup>

Cellulose, which is the naturally occurring polymer of glucose, is widely distributed in nature. In purified form, cellulose serves as the raw material for the production of a series of derivatives which are good adhesives. Raw-material cellulose is usually derived from cotton linters or from wood pulp which has been carefully purified to remove the lignin associated with it in wood. Native cellulose consists of linear chains of repeating glucose units with the following unit structure:



As may be seen from this structural formula, the individual glucose units of cellulose contain three alcohol groups which are available for reaction. Esterification with nitric acid results in the formation of cellulose nitrate, often erroneously referred to as nitrocellulose.

#### CELLULOSE NITRATE

The degree of esterification of cellulose with nitric acid, as well as the extent of hydrolysis of the cellulose chains, permits the preparation of a wide range of cellulose nitrate derivatives ranging from highly nitrated derivatives suitable as explosives to those of lower molecular weight and lower extent of nitration which are used as lacquers for protective coatings.

Cellulose nitrate for adhesive purposes contains approximately 12 per cent nitrogen and is usually supplied as a solution in strong organic solvents in combination with some plasticizing modifier. Combinations of cellulose nitrate with other resins and modifying agents have been cited in numerous patents; insofar as laminating applications are concerned, however, cellulose nitrate adhesives have been limited to specialty uses because of the high solvent content of the cement and the flammability of the adhesive.

#### CELLULOSE ACETATE

The reaction of cellulose with acetic anhydride results in the formation of cellulose triacetate. This fully acetylated form is only sparingly soluble except in chlorinated solvents, and the commercial forms of cellulose acetate are produced by the subsequent hydrolysis of the triacetate to a product of a lower acetyl content.

As with cellulose nitrate cements, cellulose acetate adhesives are usually supplied in strong solvent solutions in combination with plasticizers and other modifying agents. Their chief use has been as specialty adhesives in the bonding of porous materials such as paper

and leather. The limitations of cost and solvent system have restricted their use in the production of commercial laminates. Recent developments<sup>70</sup> in laminating technique using cellulose acetate molding powders and "squeezing" these into the fabric may overcome these difficulties.

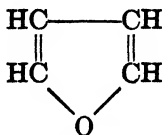
### LIGNIN

The binding material for cellulose fibers in wood is the naturally occurring material, lignin. The chemical structure of natural lignin has not been completely determined.

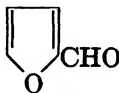
Since it is a by-product of the papermaking process, however, lignin is both cheap and available in large quantity. For this reason, extensive investigations have been carried out for utilizing this abundant raw material in adhesive applications and for the production of laminates. Commercial paper-base laminates<sup>71</sup> impregnated and bonded with lignin are currently available. Such products are all dark colored. Attempts have been made to use lignin as a modifier and extender for phenol-formaldehyde adhesives, and such combinations reduce the thermoplasticity of the lignin. The variability of lignin as a by-product has made it difficult to standardize adhesive formulations for commercial bonding operations, but the incentive for the utilization of this material should result in the practical utilization of lignin in the field of plywood bonding on a large scale.

### FURANE RESINS

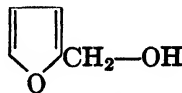
There are two derivatives of Furane (A) which have been used for the production of resins useful as adhesives in the manufacture of laminates; furfuraldehyde (B) and furfuryl alcohol (C).



A. Furane



B. Furfuraldehyde



C. Furfuryl alcohol

Furfuraldehyde is a low-cost material which is usually derived from agricultural wastes such as oat hulls and corn cobs. It is available commercially in a high degree of purity as a clear liquid with a boiling point of 161.7°C.

As a raw material for the production of adhesives it is usually reacted with phenol. In such reactions furfural behaves as aldehyde to form

dark-colored resins which can be thermoset in the normal way with heat. Phenol-furfural resins have been widely used for molding applications because of their peculiar flow characteristics. During the preliminary heating of intermediate stage condensation products, the resins of phenol furfural exhibit excellent flow and slow condensation advance until the threshold temperature of approximately 325°F is reached. At this threshold temperature, however, the condensation proceeds with great rapidity to the finally cured infusible insoluble state. This characteristic has restricted the usefulness of such resins in the bonding of wood, since the final curing temperature is rather high for unimpregnated laminas. On the other hand, cloth-base and paper-base laminates have been produced with phenol-furfural resins in considerable quantity.

Such laminates, although dark colored, exhibit acid and alkali resistance superior even to the conventional phenol-formaldehyde laminates. Their durability, heat resistance, and electrical properties are entirely comparable with phenol-formaldehyde laminates.

Furfuryl alcohol will undergo resinification in the presence of acidic catalysts to form thermoset polymers. The cross-linking mechanism for such thermosetting has not been completely clarified. Furfuryl alcohol will also react with urea-formaldehyde monomers to produce light-colored condensation products which are capable of resinification. These reactions \* are laboratory developments at the present time and have not yet made their appearance in commercial laminated products.

#### POLYURETHANES

This class of compounds was developed in Germany during World War II and used to a limited extent as protective coatings and foaming agents as well as adhesives for the assembly of wooden aircraft and similar structures. The glue lines derived from the polyurethanes are nonbrittle and very resistant to weathering as well as to hot and cold water. Polyurethane adhesives are also gap-filling. The polyurethanes have the disadvantage of being toxic, and, therefore, specialized techniques of manufacture and application are required.

The system consists of the reaction product of an isocyanate and an alcohol polymerized to form a polyurethane which is subsequently

\* Unpublished communication, Dunlop and Stout of Quaker Oats Co., Chicago, Ill.

cross-linked with a polyester resin derived from adipic acid or adipic acid-phthalic anhydride polymer.

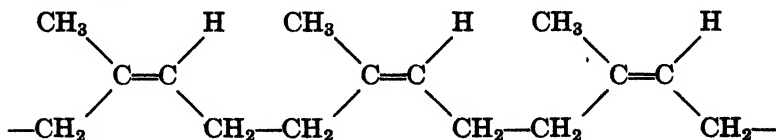
Typical of the polyurethanes used as adhesives is "Polystal U-11 glue" which is a 50-70 per cent solution in ethyl acetate of the polyurethane prepared by reacting a mixture of 2,4 and 2,6 tolyl di-isocyanate with trimethylol propane and 1,3 butanediol. This solution is activated with "Desmophen 900," a polyester of adipic acid and hexanetriol. The cross-linking is accelerated by catalysts such as ammonium chloride or urea.

The volume of polyurethanes used in wartime Germany was small, and their future in a peacetime economy will depend on whether their outstanding characteristics are sufficient to overcome the disadvantages of toxicity and application difficulties.

#### RUBBER-BASE ADHESIVES

The use of natural and synthetic rubbers and their derivatives in adhesive compositions has been widespread. Probably the first laminating use of rubber adhesives was described in 1823 by MacIntosh who obtained a patent on the cementing of two fabrics with a rubber solution to render them waterproof. Developments in recent years have been directed toward the use of synthetic rubbers and rubber derivatives under the impetus of the shortage of natural rubber during World War II. Adhesives incorporating rubber-like components have the advantage of providing a glue line which has a certain degree of elasticity and, therefore, is able to distribute localized strains on an adhesively bonded joint. The second outstanding characteristic of rubber-base adhesives is their high specific adhesion to surfaces such as metals and plastic materials which are ordinarily difficult to bond.

A detailed discussion of the chemistry of natural and synthetic rubber is beyond the scope of this work, and the reader is referred to several excellent publications in this field.<sup>72-74</sup> For our purpose it is sufficient to describe rubber as principally a hydrocarbon with the empirical formula  $C_5H_8$ . The structural composition of the linear chains which are entangled to form natural rubber is generally accepted to be the following:



In adhesive compositions crude rubber is sometimes used, but more frequently the rubber is vulcanized either before preparation of the adhesive or in the glue line at the time of bonding. The vulcanization process was discovered by Charles Goodyear in 1839 when he heated together an intimate mixture of rubber and finely divided sulfur. Since that time numerous other materials have been employed for achieving the same effect. Sulfur monochloride, peroxides, and polynitro compounds are used. Accelerators, complex organic compounds, determine the rate and extent of the vulcanization reaction.

Vulcanized rubber is greatly increased in tensile strength and elasticity, is nontacky and less sensitive to or soluble in most solvents, and is nonthermoplastic. No single theory explains all the properties of rubbers during vulcanization, but it is generally agreed that cross linking between chains occurs together with a reduction in the unsaturation of the rubber molecules. The classical theory postulates primary valence linkage through a single sulfur atom.

#### RUBBER LATEX

Natural rubber is obtained as rubber latex which is a finely dispersed colloid of the hydrocarbon polymer. The rubber latex as obtained from the tree can be stabilized and used as a component of adhesive compositions. Since synthetic-rubber polymers, particularly those of butadiene rubbers, are prepared by emulsion polymerization, their latices can also be used in a similar manner. Rubber latex may be used in combination with other colloiddally dispersed materials in the preparation of laminating adhesives. The combination of rubber latex, blood albumen, and casein has enjoyed considerable application as a metal-to-wood adhesive. Vulcanizing agents may be incorporated in the continuous phase of the latex to provide for vulcanization of the film which is obtained when the water is lost from the glue line.

#### RUBBER SOLUTIONS

The commonest forms of rubber cements are solvent solutions of rubber in solvents such as benzene, ethylene dichloride, solvent naphtha, or gasoline. Such cements have excellent tack and for laminating purposes are used principally for the bonding of rubber and leather. By proper formulation they can be made "self-vulcanizing," that is, vulcanizable in the glue line at room temperature.

Rubber-base adhesives have been combined with numerous resins, starches, and inorganic materials, depending on the final properties desired. Loading materials, such as carbon black, colloidal clays, zinc

oxide, barium sulphate, and calcium carbonate, are used to increase the density and strength of the glue line as well as to reduce its cost. Cumaron-indene resins, ester gum, rosin-modified phenolic resins, and such are added as tackifiers and to improve the water resistance of the rubber film.

#### CHLORINATED RUBBER

When chlorine reacts with rubber in solid form or in solutions in chlorinated solvents, hydrogen chloride is evolved at the beginning of the reaction as hydrogen atoms are replaced by chlorine, and at the same time chlorine is added to the double bonds to yield finally a chlorinated rubber containing two-thirds chlorine by weight.

Chlorinated rubber is soluble in aromatic hydrocarbons and a variety of ketones, esters, and chlorinated solvents. When suitably plasticized, chlorinated rubber will yield adhesives particularly suitable for bonding metal to rubber. Chlorinated rubber is stable at temperatures below 135°C, is nonflammable, and is outstanding in acid and alkali resistance.

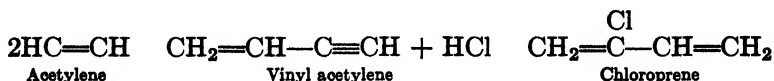
#### RUBBER HYDROCHLORIDE

At low temperatures, anhydrous hydrogen chloride will react with rubber in solution to produce rubber hydrochloride by the addition of HCl to the double bonds.

In thin transparent sheets this product is familiar as a packaging material (Pliofilm). In solvent solution, rubber hydrochloride is used in combination with resins and waxes as a heat-sealing adhesive for the lamination of paper, and, in vulcanizable compositions, it is used for bonding metals and rubber.

#### NEOPRENE CEMENTS

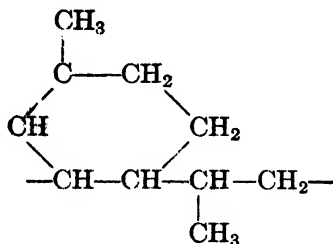
Neoprene, or more properly, polychloroprene, is a synthetic rubber produced by the polymerization of chloroprene derived from the reaction of HCl with monovinyl acetylene.



Vulcanizable cements based on polychloroprene are widely used for the bonding of leather, rubber, and metals to rubber. The cured adhesive is characterized by excellent solvent and oil resistance as well as resistance to oxygen and aging deterioration.

## RUBBER ISOMERS

The treatment of rubber with sulfuric or sulfonic acids or with chlorostannic acid results in isomerized or "cyclicized" rubber isomers. These products resemble in many ways the natural rubber isomers, balata and gutta-percha. The unit structure is probably a ring formation:



The properties of isomerized rubber depend on the amount and type of acid catalyst as well as the time and temperature of treatment. Variations from vulcanizable soft stocks to hard thermoplastic resins are possible.

"Cyclized" rubbers are soluble in strong organic solvents, and such solutions are used as cements, particularly for rubber to metal bonding. Rubber components of laminates are frequently surface "cyclicized" by treatment with strong acids to prepare the surface for bonding with adhesives such as the phenol or resorcinol formaldehydes.

The formation of rubber isomers in the presence of phenols has resulted in products which are useful as laminating adhesives for metals and regenerated cellulose as well as vulcanized rubber. Only a small proportion of the phenol is chemically bound, and such phenol modified rubbers can be reacted with aldehydes such as furfural or formaldehyde.

## SILICONE RESINS

The use of this generic group of resins for laminating is relatively new, the first laminates of glass cloth bonded with silicone resin being exhibited for the Society of Plastic Engineers, January 7, 1946. The silicones are characterized by excellent electrical properties and, most important of all, stability at service temperatures considerably higher than conventional organic resins.

The structure of the finally cured silicone resin is analogous to sand or quartz, since it comprises a network of interconnected chains of alternating oxygen and silicon atoms in which each silicon atom bears



one or two simple alkyl or aryl organic groups. The starting materials for the preparation of silicone resins are organosilicon halides made by reacting the appropriate Grignard reagent with silicon tetrachloride or by the catalytic reaction between elementary silicon and the organic halide.

TABLE 2-4

Fabric Resin	ESS 261 Fiberglas DC 2103
Flexural strength, psi	
$\frac{1}{8}$ -in. panel, flatwise	22,000
$\frac{1}{8}$ -in. panel, edgewise	28,000
Tensile strength, psi	15,000
Impact strength, ft-lb per in. notch	
Flatwise	13.0
Edgewise	10.0
Bonding strength, lb	
$\frac{1}{2}$ -in. panel	1,250
Water absorption, 24 hr per cent	
$\frac{1}{8}$ -in. panel	0.21
Dielectric strength	
$\frac{1}{8}$ -in. panel, volts per mil	250
Dielectric strength, step by step	
$\frac{1}{2}$ -in. panel, kilovolts	50
Power factor, (D-24/25), per cent	
1 mc	0.51
100 mc	0.97
Loss factor, (D-24/25), per cent	
1 mc	1.95
100 mc	3.15
Insulation resistance, wet, megohms	120,000
ASTM arc resistance, sec	300
Heat distortion, °C	250

Courtesy Dow Corning Corp.

The fractionation of the reaction products yields the individual compounds. A mixture of the di- and trihalide is then hydrolyzed with water to give hydroxysilanes, usually called silicols which then condense by the elimination of water to form linear chains with few cross linkages. The silicols are actually seldom isolated as such.

Such low-molecular-weight silicone resins are soluble in organic solvents, and the solutions are used as varnishes for the impregnation of the sheets to be laminated.

After the removal of solvent, the final cure of silicones is accomplished in the conventional way under heat and pressure to give the insoluble infusible high-molecular-weight resin.

In practice, a relatively large proportion of trihydroxy- to dihydroxy-silanes is used to improve the curing speed. Curing catalysts, such as lead naphthenate, lead stearate, zinc chloride, and benzoyl peroxide are employed. Co-condensations of methyl silicols with phenyl silicol have yielded the most interesting laminating resins.

The materials which are bonded with silicone resins are usually inorganic, glass or asbestos cloth, mat, and so on, in order to take the fullest advantage of the high heat endurance of these resins. Table 2-4 shows the properties of a glass-cloth laminate.

### **SPECIAL ADHESIVES**

A number of proprietary adhesives have been developed on a commercial scale for the bonding of metals. Their importance in the structural laminate field justifies their inclusion here by trade name, since their exact composition has not been disclosed in most instances.

The problem of bonding metal to metal is satisfactorily solved when metallic solders can be employed. Welding is the easiest solution when heavy-gage stock of unsolderable metals are involved. For the joining of thin light-metal alloys, however, the conventional joining with rivets is expensive and results in joint strength well below that of the joined parts. The ideal solution would be an adhesive bond to provide a joint which would be stronger than the single thickness of the metal member. Except in the case of very thin-gage metal sheets this ideal has not been achieved.

The bonding of metal to other materials such as wood, rubber, plastics, and paper is important in the production of laminated constructions, particularly in the aircraft field.

The adhesives which are described briefly here are, we trust, the forerunners of improved bonding agents for metals. For detailed information it is suggested that the manufacturer be consulted.

#### **“Redux” \***

The “Redux” process is based on the use of two separate components, a clear reddish-brown low-viscosity solution of a thermosetting adhesive and a thermoplastic vinyl resin powder. The “Redux” liquid is applied to the clean metal surface, and, while this coating is wet, the surface is saturated with the “Redux” powder. After sufficient open assembly to allow the evaporation of the solvent, similarly coated metal

\* Aero Research, Ltd., Duxford, England and Resinous Products and Chemical Co., Philadelphia.

surfaces are bonded under heat and pressure. In metal-to-wood or metal-to-plastic joints, Redux liquid alone is applied to the latter surface.

Curing schedules are dependent on the temperature, 15 min at 300°F being typical. Optimum glue-line thickness is between 0.002 and 0.006

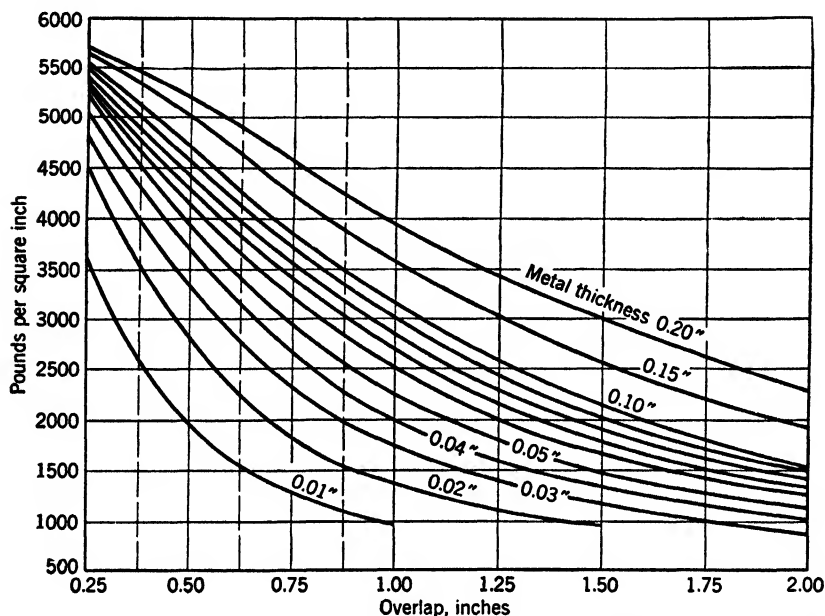


Fig. 2-1. Relation of Ultimate Shear Strength, Metal-to-Metal Redux Joints, According to Overlap and Metal Thickness. (From de Bruyne Nomogram)

in. with pressure requirements approximately 250 psi to achieve these dimensions.

The relations of joint dimensions, metal thickness, and shear strength are shown in Fig. 2-1.

"Redux" joints show undiminished strength at service temperatures up to 160°F, although above this temperature the bond strength is reduced. Recovery on cooling is excellent. "Redux" bonds are non-corrosive and show good resistance to solvents, salt-water spray, and vibration fatigue.

#### "CYCLEWELD" \*

The "Cycleweld" adhesive has only been described as a modified form of rubber. The adhesive solution is applied to the clean metal

\* Chrysler Corp.

surface by brushing or spraying to build up the desired adhesive film thickness. After evaporation of the solvent, the assembly is bonded under heat and pressure.

Curing schedules are 10–15 min at 325°F under a pressure of 200–300 psi. “Cycleweld” adhesive can be oven-cured as a metal primer, and subsequent gluing to wood, and so on, can be carried on with assembly adhesives such as room-temperature-setting resorcinols.

Adhesive strengths on sheet aluminum are of the order of 3000 psi, and “Cycleweld” joints exhibit good durability and resistance to vibration fatigue.

#### REANITE \*

This group of proprietary metal adhesives has been described as an intimate mixture of rubber, weak acids, and solid salts of strong acids. The adhesive solution is applied to the metal, thoroughly air-dried and bonded at a schedule of 15 min at 290°F. Shear strengths ranging from 1000 to 3000 psi have been obtained.

#### “METLBOND” †

A group of metal adhesives which has been developed under this trade name is described as synthetic-resin-rubber adhesives. They range from compositions requiring low pressures and curing schedules of 330°F for 20 min to materials cured at 100 psi at 250°F. Shear strengths in excess of 3000 psi have been obtained in aircraft constructions.

#### “ARALDIT” ‡

This group of synthetic adhesives for metal and plastic bonding, of undisclosed structure but perhaps a carbazole type, has been reported from Switzerland as commercially offered materials.

Published information indicates that the adhesive, of limited storage stability, is supplied as a light-colored hard resin in bar or powder form. At 105°F the material softens and may be brush-spread at 180–210°F, whereas at 250°F the resin is quite fluid. Curing schedules are of the order of 40 min at 390°F for metal-to-metal joints. Only contact pressure is necessary.

“Araldit” bonds are unimpaired by exposure to benzene, gasoline,

\* U. S. Stoneware Co.

† Consolidated-Vultee Aircraft Corp.

‡ Ciba Corp., described in *Schweiz. Arch.* (1946) 12, 113, and *Brit. Plastics* (July 1946) 357.

acetone, or water below 180°F. Shear-strength values (test specimen 1-in.-wide, ½-in.-overlap aluminum alloy) are given as 3275–3000 psi over the temperature range—70° to 195°F. The shear strength at 212°F in this construction is given as 2700 psi which falls to 1000 psi at 250°F.

At the present time, "Araldit" adhesives are not available in the United States. European reports, however, indicate that this special adhesive provides excellent bonds on light metals. Such bonds are claimed to have good aging characteristics and are odorless, tasteless, noncorrosive, and nontoxic. The slow-curing rate at high temperatures restricts the potential uses of this adhesive.

The previous listing is by no means complete, but it includes those products which have been recognized as pioneering developments in an adhesive category where there is still much to be done before an entirely satisfactory solution to the metal bonding problem is achieved.

#### GENERAL METHODS OF APPLICATION

##### PREPARATION OF SURFACES TO BE JOINED

In order to realize the full strength characteristics of an adhesive, it is necessary not only to consider the properties of the adhesive which is chosen for a particular bonding application, but also to consider carefully the preparation of the surfaces to be joined in order that these surfaces may present an optimum condition. Only in this way can the full potentialities of the system of laminas and adhesive be realized.

The first factor to be considered in the preparation of surfaces to be glued with an adhesive is the problem of proper fitting. In general, adhesives are not good structural materials in bulk, and the thinner the glue line which is finally achieved, the nearer the joint will reach the ultimate in strength properties. Although certain adhesives have gap-filling characteristics, there is no substitute for a well-fitting adhesive joint.

##### PREPARATION OF METALS

The metal surfaces which are ordinarily used as members of laminated constructions are products of a rolling mill or foil rolling machinery. Although some of these metals, notably stainless-steel sheets, have been abrasive-polished by the manufacturer, all too frequently the metal surface is heavily contaminated with oil or other

lubricant. Such surface films are usually removed before bonding operations, since they almost invariably interfere with proper adhesion of the adhesive to the metal.

A number of cleaning methods have been investigated and are described here in their order of effectiveness:

A. The following treatment, recommended in British Specification DTD 915 has been found to be very effective in preparing Alclad aluminum for bonding where maximum shear values are desired:

1. Degrease sheets by solvent wipe or vapor degrease, using solvents such as trichlorethylene and carbon tetrachloride.

2. Immerse in an acid bath for 20 min at 140–150°F, prepared as follows: 1 lb sodium dichromate; 4.5 lb concentrated sulfuric acid; 14 lb water.

3. Rinse in cold water and then in hot water.

4. Dry, using hot air or oven, if necessary.

B. Abrasion of the surface with steel wool, sandpaper, emery paper, or by sand blasting, may also be employed. The metal should be carefully flushed with water to remove all abrasion particles and allowed to dry before adhesive is applied. It may be necessary to wipe the surface several times with a clean cloth to remove fine abrasion particles.

C. Another method which yields very satisfactory results consists of the following:

1. Wipe surfaces with a clean cloth soaked in acetone.

2. Dip the metal in hot carbon tetrachloride.

3. Dip the metal in cold carbon tetrachloride, remove, and air-dry.

It is important that all solvent be allowed to evaporate from the metal surfaces before the adhesive is applied.

A simple method of determining whether the metal has been satisfactorily cleaned is to flow water over the surface. If the water forms a continuous film, the metal can be considered sufficiently cleaned for bonding.

Recently, two U. S. Army Air Force Specifications, 20032 and 20034, list other methods of preparing metal surfaces for bonding.

## PREPARATION OF WOODEN SURFACES

The treatment of a wooden surface in preparation for gluing depends to a considerable extent on the thickness of the individual laminas under consideration. The ordinary veneers for bonding into plywood or into laminates whose individual layers are thinner than approximately  $\frac{1}{8}$  in. are prepared for bonding by adjusting their moisture con-

tent into the proper range for the adhesive which is to be used. Such thin wood veneers are cut on rotary lathes or veneer slicers and subsequently dried, trimmed, and spliced into sheets of the proper size for the bonding operation. Their surface characteristics are usually fixed by the standard of the veneer-cutting operation, and further surface preparation is usually not practical. The veneer-cutting operation, therefore, requires careful control in order to obtain smoothly cut veneers of uniform thickness and free of defects which may be caused by poorly adjusted or poorly operated veneer-cutting machinery.

In the case of the lamination of heavier wooden members as in laminated timber structures, the individual laminas should be prepared for gluing after the drying operation which adjusts the moisture content of the individual layers. This is accomplished usually by mechanical planing. The surface planing accomplishes two functions: (1) It removes surface imperfections which may interfere with the intimate fitting of the surfaces to be glued, and (2) it exposes a fresh wooden surface for the bonding operation. For the latter reason, it is desirable that the final planing operation be carried out as shortly before assembly of the lamination as possible. Planing operations should always be carried out with properly adjusted tools, since an improperly adjusted planer may result in a burnishing of the surface. A burnished wooden surface not only is very smooth which results in the closing of pore spaces, which may contribute something to the bond as a result of mechanical adhesion, but also is usually the result of local overheating of the wooden surface by the planing tool. Such overheating results in dehydration of the surface cellulose fibers and reduces the specific adhesion of the surface for the adhesive. A similar burnished surface is often found in hot-pressed plywood surfaces which are next to the cauls of a hot press, and, if such surfaces are to be later bonded as part of a laminate, it is usually advisable to remove this surface burnish by sanding. Wherever possible, however, planing or similar cutting finishes are preferable to sanding as a preparation for gluing operations.

#### PREPARATION OF CLOTH

The preparation of textile fibers for incorporation in laminated constructions presents specialized problems. In some cases, oils are necessary to the spinning operation, and with some adhesives this spinning oil must be removed in order to obtain proper bonds between the adhesive and the textile fiber. It is suggested that both the adhesive manufacturer and the supplier of the cloth for laminating be consulted regarding specific combinations. Similar problems arise in the use of

glass cloth or spun-glass fibers in laminated combinations. With glass cloth, however, the removal of spinning oils or size is considerably simplified by the high-temperature resistance of the fiber and such oils are usually removed by baking the cloth at elevated temperatures.

In some cases, sizing treatments will enhance the specific adhesion of the cloth for the laminating adhesive, and here again the manufacturer should be consulted.

### PREPARATION OF OTHER MATERIALS

The papers used as laminating bases are usually manufactured with characteristics which require no further treatment. Surfaces of leather, linoleum, and such miscellaneous materials, should be clean and oil- or grease-free in order to be properly bonded. It is frequently desirable to assemble laminates in a secondary gluing operation, for example, the assembly of paper-base or cloth-base laminate to plywood in the manufacture of table or desk tops. Since the surface of such laminates is usually highly polished from the laminating operation, for best adhesion it is desirable to abrade the "plastic" surface to remove this polish before the secondary gluing operations are carried out.

### METHODS OF APPLYING THE ADHESIVE

#### BRUSHING

For comparatively small areas or for assembly gluing operations, the adhesive is sometimes applied by brushing with stiff-bristle brushes or from serrated paddles or hand-operated extrusion guns. These methods are seldom applicable, however, to large-scale commercial operating procedures.

#### SPRAY-GUN APPLICATION

The use of a spray gun to apply adhesive is usually limited to cases where repeated applications are necessary in order to build up the required adhesive-film thickness or to cases where the handling of the member to which adhesive is to be applied is difficult. The spray-gun method is seldom used in large-scale operations, because (1) the amount of solvent for the adhesive which is required to reduce the solution to a suitable spraying viscosity introduces solvent which must subsequently be evaporated; (2) the overspray results in the waste of a considerable portion of the adhesive; and (3) suitable spray booths or other ventilating equipment are necessary to provide disposal of the solution vapors.



### DOCTOR BLADE

For the continuous application of adhesive to one side of a flexible material, the system of doctor blade and blanket has been widely used. The arrangement of equipment is similar to that used in the coating of paper or cloth. The web of material to be spread with adhesive is drawn continuously over a supporting blanket, usually rubber, which is an endless belt, moving on a roller system. Against this resilient backing, the web to be coated is drawn across the edge of a doctor blade, and the adhesive is fed to a pool in front of this blade.

### DIP TANK AND NIP ROLLS

The most common system for the impregnation and application of adhesive to both sides of laminas when the member is flexible, as well as continuous as in the case of a paper, is the dip-tank and nip-roll scheme. In this system, the continuous web is fed over a roller system and completely submerged in a tank containing the adhesive solution. The web leaving the tank is fed through a pair of rollers which are adjusted to remove the excess adhesive and provide a uniform spread. The amount of adhesive applied can be varied in such a system by changing the gap or pressure between the nip rolls and also, of course, by varying the solids concentration of the dip bath. This system is used extensively in the preparation of paper-base and cloth-base laminates, and many minor variations are in common use.

### ROLLER SPREADING

The application of adhesive with roller spreaders is most common when rigid or predimensioned laminas are involved. In a roller spreading system, the adhesive is distributed over a roller from a reservoir by the action of a doctor roller. The adhesive is transferred from the application roller to the bonding surface as the laminas are passed over it. Four standard roller systems are shown in Fig. 2-2.

When relatively heavy spreading rates of adhesive, 60 to 100 lb of liquid adhesive per 1000 sq ft single glue line, are involved, the spreader rolls are usually metal, and the surface is corrugated. For the lighter spreading rates as for synthetic-resin adhesives in the region of 20 to 50 lb of liquid adhesive per 1000 sq ft of single glue line, the spreader rolls are usually rubber-covered and corrugated (Fig. 2-3). The rubber covering permits more even spreading rate by adjustment of the doctor roll pressure.

For manually fed roller spreaders such as in plywood operations, the average spreading speed is approximately 75 lin ft per minute, although

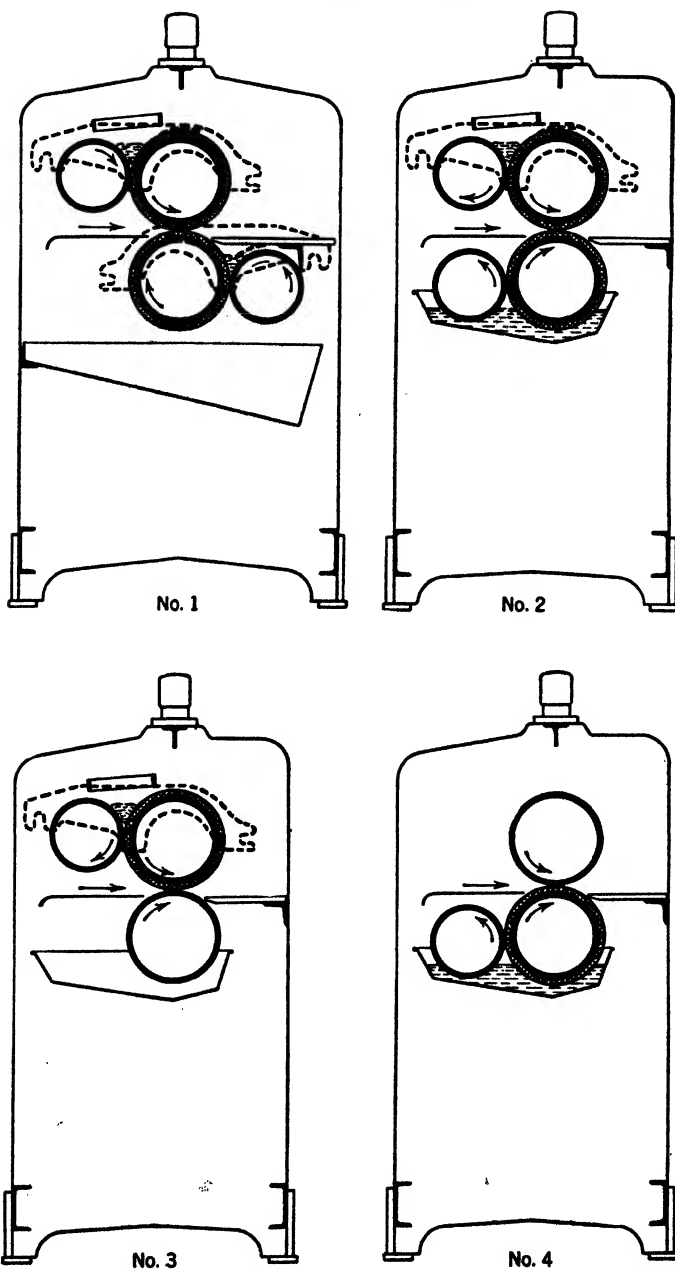


FIG. 2-2. Various Arrangements of Rollers and Glue Reservoirs in Mechanical Glue Spreaders. (Courtesy Black Brothers Company)

in some operations such as Douglas fir, a speed of 150 lin ft is not uncommon. In order to obtain even spreading at very light spreading rates, slower speeds are commonly used.

Although wide viscosity variations in the adhesive are encountered in commercial spreading operations, an absolute adhesive viscosity of 20–30 poises is usually considered optimum. The upper limit for successful spreader operation, particularly with rubber roll spreaders, is



FIG. 2-3. Rubber-Roll Glue Spreader Shown in Use on Wooden Assemblies.  
(Courtesy Cabinet Craft Corporation)

approximately 200–300 poises. Some difficulty may be encountered with such high-viscosity adhesives, however.

#### DIMENSIONING OF FILMS

Film-type adhesives are supplied in rolls and are prepared for use merely by cutting from the roll a piece of the proper dimensions. Commercial dimensioning equipment is available for such work.

#### LIMITS OF ADHESIVE SPREAD

Adhesive spreading rates are usually expressed as pounds of adhesive solution per 1000 sq ft of glue line. Single spreading refers to the application of adhesive to only one of a pair of mating faces, and double

spreading is the term used when the adhesive in a glue line is equally divided by application to the two mating surfaces. Adhesive spreading rates are occasionally expressed as pounds of solids per 1000 sq ft of glued area, but in such cases the spreading rate should always be specifically labeled as applying to adhesive solids. In the Douglas-fir plywood industry, the spreading rates are expressed as pounds of liquid adhesive per 1000 sq ft of three-ply panel; that is, the basis is 2000 sq ft of glued joint. This convention is restricted to Douglas-fir plywood industry.

In the interest of economy and also to obtain as thin a glue line as possible, it is important to keep adhesive spread to a minimum consistent with maximum bond strength. There are several factors which influence the lower limit of adhesive spread:

1. The first is the gap to be filled which, of course, depends on the smoothness and fit of the mating surfaces which are to be bonded. The adhesive spread should always be sufficient to provide a continuous film between the two adherent surfaces without leaving spaces for air bubbles or other film discontinuities.

2. The absorbency of the laminas for the adhesive is, of course, an important factor influencing the spreading rate. Where highly absorbent materials are to be bonded, it is often customary to provide a sizing coat of the adhesive which is dried and may even be cured before the final bonding adhesive is applied to the joint.

3. The lower limit of adhesive spread is also defined to a considerable extent by the flow characteristics of the adhesive itself under the conditions of bonding. Adhesives with long flow periods or which are bonded under conditions of slow heat penetration require heavier minimum spreads than faster-curing materials.

#### CONDITIONS OF BONDING

In cases where the flow period of the adhesive is long under the conditions of bonding and the surfaces to be joined at least partly porous, inadequate spread will result in a "starved joint." The flow characteristics of the adhesive will depend not only on the rate of curing as determined by the resin characteristics and the heat input, but also, in a number of cases, on the fluxing action of moisture or solvent which may be either a part of the adhesive film or present in the adjacent adherend layers.

The minimum adhesive spread for a given construction should be determined experimentally for each operation, and during production

frequent checks on the actual adhesive spread should be made by weighing standard surface sections before and after spreading.

### DRYING

In many laminating operations, it is imperative that the solvent in which the adhesive is applied be evaporated or removed before the laminate can be finally bonded. In other cases, it is essential that the laminate be brought under pressure while the adhesive system is still "tacky" and contains a substantial portion of its solvent.

The time interval between the spreading of the laminate layers and their assembly under pressure is usually referred to as the assembly time. Open assembly refers to the handling or storage of spread layers open to free atmospheric circulation, and closed assembly to the piling solidly of the spread layers, usually in the same relation in which they are finally to be bonded. Most adhesive systems have well-defined minimums and maximum open- and closed-assembly time limits. These limits are available from the adhesive manufacturer for each given set of conditions. It must be remembered, however, that the factors of temperature, absorbency of the laminas for the adhesive solvent, moisture content of the ambient atmosphere, size and shape of the construction, and also the conditions under which the laminate is to be bonded, all influence these assembly time limits.

In cases where the solvent must be removed from the adhesive before assembly and bonding operations can be carried out, it is often possible to store the spread layers on open racks and allow the drying to take place at room temperature by evaporation. In commercial operations where it is necessary to accelerate this step, oven drying is often carried out. In the cases where continuous laminating allows the carrying of the spread web through a drying tunnel or drying chamber, this technique is used. In force-drying operations, care must be exercised in establishing the time and temperature limits of the drying operation in order to avoid a precure of the adhesive film.

### METHODS OF APPLYING PRESSURE

The use of pressure during any bonding operation may vary widely, depending on the particular adhesive under consideration. Pressure during any bonding operation has several functions. The coating of adhesive in the joint must be reduced to a thin continuous glue line of uniform thickness, and in most cases it must be distributed uniformly

over the joint. Most forms of adhesive spreading are likely to be uneven, and in the case of glue-roll spreaders the adhesive is actually applied as a series of ridges of adhesive spread. Pressure also serves to eliminate any imprisoned air and to force the adhesive, during the flow period, into irregularities or pore spaces in the surface of the materials to be bonded. This is particularly important when only one mating surface is spread with adhesive. Pressure during bonding also serves to hold the two sides of the joint in an uninterruptedly fixed position during the period required for the adhesive to cure or set. For maximum strength, the pressure should be maintained substantially at a fixed level during such bonding operations.

The specific pressure, usually stated in pounds per square inch, required for a given assembly depends not only on the character of the adhesive to be used, but also on the characteristics of the individual laminas. In some instances, contact pressure is adequate for the bonding operation, and the other extreme is high-pressure laminating with paper-base or cloth-base phenolic or melamine laminates where specific pressures may be as high as 1500 psi. Pressure requirements will depend not only on the flow characteristics of the adhesive, but also on the construction and composition of the individual laminate layers. Where the surfaces to be bonded can be brought into close-fitting uniformity over the bonding area, the pressure requirements will be at a minimum for the particular adhesive which is being used. Where the laminate consists of several layers and where each layer may consist of several pieces, which may be cut to accepted commercial standards for thickness but still vary by some thousandths of an inch, the pressure requirements will be considerably higher in order to achieve the properly thin glue line at the area of greatest glue-line thickness. In the case of curved assemblies or assemblies in which the individual laminas may be warped or exert a back pressure, the effective pressure on the glue line may be considerably less than that applied externally to the assembly, and such factors should be taken into account when setting minimum pressure standards.

Described briefly here are the most common methods of applying pressure during a bonding operation.

#### CONTACT OR ROLLER PRESSURE

Laminating under the low specific pressures which can be achieved with rollers or between a web under tension and a roller has until recently been confined to the manufacture of multilayer paperboards and similar materials with adhesives of very high tack. Such pressure

systems are used in the manufacture of corrugated paperboard and solid fiberboard laminates. The development of the so-called contact laminating resins has extended these pressure systems to the continuous manufacture of paper-base and cloth-base laminates in which the supporting web is cellophane or coated paper. The pressures obtained in such a laminating system are of a very low order and are actually only sufficient to bring the flexible adjacent layers into contact.

### CLAMPS AND SCREWS

One of the commonest methods of applying pressure, particularly in the woodworking industry, is by the use of screw clamps or screw jacks. The pressure applied by the tightening of a screw or nut, of course, requires distribution over the area to be placed under pressure. In order to obtain uniform pressure when several screws are required for a given assembly, the screws or nuts are usually tightened with torsion wrenches, or at least the pressure is judged during a manual operation. In some cases, motor-driven torsion wrenches are employed.

Retaining clamps are often used as an adjunct to hydraulic presses, particularly in cold-press plywood operation, where the assembly is compressed under hydraulic pressure in a cold press as described below, and the bale or assembly is maintained under pressure by the use of retaining clamps. This combination is illustrated in Fig. 2-4.

Another form of applying pressure by means of an inclined plane is included here merely for completeness. This system involves the use of wedges or cams to exert pressure on an assembly. Although not particularly flexible, such pressure devices are sometimes encountered in conjunction with the use of stiff dies or other formed platens.

### PISTON PRESSURE

The pressure exerted by pneumatic or hydraulic pistons has several distinct advantages: It is measurable and, under automatic control, can be continuous. Hydraulic pressure can usually be quickly and easily applied and is particularly suited to repetitive operations on a short-time cycle.

Pneumatic piston pressure is frequently encountered where light work is involved but because of compressor limitations is seldom used at piston pressures over approximately 100 psi.

Hydraulic piston pressure is by far the most widely used pressure device in the production of laminated constructions. The commercially available equipment ranges from the small single-piston presses which are used for the room-temperature bonding of plywood to the multiple

piston presses used for high-pressure laminating. Figure 2-4 shows the former with a bale of work in place. Figure 2-5 shows a typical 16-opening (or daylight) steam platen press together with the pumping system and automatic-control equipment, for moderate pressures up to 300 psi.

#### FLUID PRESSURE

The pressure devices outlined above all suffer from the limitation that they are unidirectional and, even with the use of rigid dies, produce



FIG. 2-4. Single-Piston Cold Press Showing the I Beams and Retaining Clamps for Keeping the Bale under Pressure after Removal from the Press. (Courtesy Kent-Coffey Manufacturing Company)

complicated pressure systems where areas of curvature through large angles are under consideration. In other words, when unidirectional pressure is applied to curved surfaces, the pressure component exerted at any point on the curve is proportional to the cosine of the angle between the direction of pressure and a perpendicular to the tangent of



the curve at the point in question. Where curved sections are under consideration, fluid or omnidirectional pressure is the solution.

The simplest form of fluid pressure is obtained by enclosing the assembly which has been laid up over rigid male dies in a flexible, not necessarily extensible, impervious bag and then exhausting the air from



Fig. 2-5. Multiple-Piston Steam-Platen Hot Press Together with Pumping Mechanism and Other Auxiliary Equipment. (Courtesy Mengel Company)

the interior of the assembly. The atmospheric pressure is then exerted over the whole area. In such cases, obviously, the maximum obtainable pressure is atmospheric and therefore limited to approximately 15 psi.

The next step in the development of fluid pressures was the enclosure of such an exhausted assembly in an autoclave and applying steam or air pressure to the outside of the rubber bag and thus increasing the available specific pressure.

Many variations of this flexible-bag or rubber-bag method are, of course, possible. The bag can be inflated against the work laid up in

female dies with the bag in the cavity and the cavity rigidly closed. Although the pressures usually used in flexible bag molding are of the order of 100 psi. maximum, because of their omnidirectional character, they are particularly effective on curved sections and have been widely used in the molding of such articles as radomes, small boat hulls, and the monocoque type of fuselages of plywood training planes. The adhesives used in such applications are usually specifically designed for the purpose.

#### CURING OF THE ADHESIVE

This section might also be entitled "Methods of Applying Heat," since in adhesive systems which reach their final state by the loss of

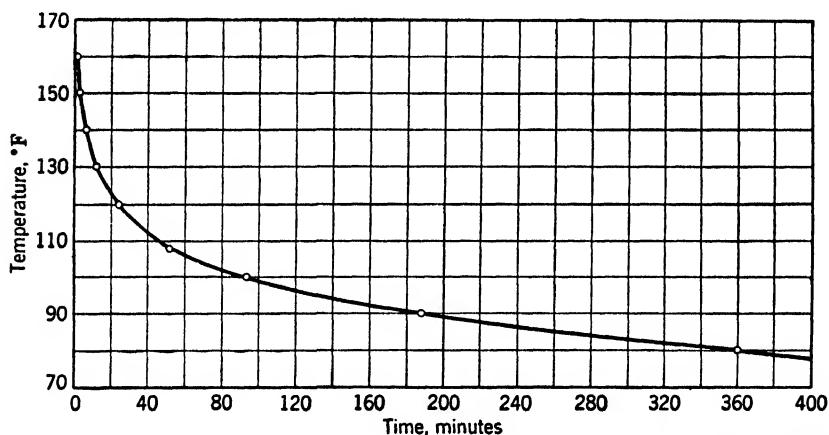


Fig. 2-6. Bonding Schedule for a Typical Resorcinol-Formaldehyde Resin Based on Glue-Line Temperatures in  $\frac{3}{16}$ -in. Birch Plywood.

solvent or by cooling, in the case of the thermoplastics, no adhesive cure in the ordinary sense is required. The term "curing" is usually applied to the chemical phenomenon of cross linking in the further polymerization and condensation of thermosetting adhesive systems. In the case of thermoset adhesives which are designed to be used at room temperature, it is only necessary to maintain the laminated assembly under pressure until at least the initial stages of curing are complete. Even with such adhesive types, however, the curing cycle can usually be greatly accelerated by the application of heat at the glue line (see Fig. 2-6).

Hot platen presses developed in Europe during the decade 1910-20 with the use of blood albumen as a wood glue in the manufacture of

plywood. The advent of synthetic-resins adhesives which required heat curing gave impetus to this development in Europe during the 1920's and in the United States in the early 1930's.

#### STEAM-HEATED PRESS PLATENS

The commonest source of heat for the cure of laminates is steam-heated platens in conjunction with hydraulic presses. Such press platens are usually accurately faced steel and are drilled to provide a labyrinth through which the steam flows. Although the assemblies for lamination are sometimes inserted directly between the hot-press platens, more often, particularly in the case of laminates where a good surface finish is required, they are introduced between the heated platens in the form of a sandwich between polished metal cauls. In the plywood industry such cauls are usually of aluminum. In the case of high-pressure laminates, stainless-steel or heavily chromium-plated steel cauls are employed. Cauls facilitate the handling of the laminates to be pressed, and they are almost invariably used when the charge between a single pair of press platens consists of more than one assembly. The use of cauls is also imperative when the press is mechanically loaded.

Mechanical loaders are simply racks which have supports at the levels which correspond to the press daylights when the press is completely open. The assemblies together with their cauls are placed on the racks and are all inserted at once when the press is down. Such a system is usually combined also with a discharge rack on which the finished laminations together with their cauls are received at the time of discharge.

Because the penetration of the heat in steam platen presses is from both sides, the efficiency of such a press is considerably better than systems which heat from one side only. Hot presses, however, are limited in the thickness of the assemblies which they can bond efficiently. Except in specialized cases, this limit is approximately 1-in.-thick sections.

There are several techniques which are used to improve the efficiency of hot presses. The first is most frequently encountered in the handling of laminates based on cloth or paper and consists of preheating the laminate either in circulating air ovens or with high-frequency heat. In this way, the temperature of the assembly is brought near the curing and flow temperature before insertion into the press, and the press time is consequently shortened considerably. The second system is known

usually as "the hot-stack technique" and is used almost exclusively when flat laminates are under consideration. "Hot stacking" is simply the piling solidly of a number of laminations as promptly as possible after discharge from the press. At the time of discharge the entire assembly has usually reached the maximum temperature and contains a considerable amount of stored heat. By solid stacking and sometimes protecting the edges of the laminate pile with cloth or other insulating material, to reduce the heat losses, advantage can be taken of this residual heat to complete the adhesive cure. In the hot-stack technique, the cure of the adhesive in the press is only carried far enough to hold the laminate together, and the stacking time and temperature will complete the cure after discharge from the hot press.

Although most hot platen presses have plane platens for the manufacture of flat laminates, steam platens can also be produced in the form of dies for simple and moderate compound curvature. Such die platen presses are used for the repetitive manufacture of curved sections such as beer-barrel staves and formed plywood trays such as the "Toastmaster" tray, and also for specialized laminates such as the blanks from which wooden golf-club heads are cut.

Steam-heated platens are probably the most frequently used of the methods for introducing heat to cure adhesive glue lines. Steam heat has the advantage of economy and is also almost the only possible method when it is imperative that the cured laminate be cooled before pressure is released. In such cases, the press platen is arranged for the introduction of water through the steam-circulating system, and in this way the platen and assembly can be cooled to room temperature fairly rapidly.

In flexible bag molding, the steam which supplies at least part of the pressure to the flexible bag in many cases is also the source of heat. When rubber bags are used, the heat input is usually controlled by using air to provide at least part of the pressure and introducing steam into the bag after the assembly has settled into place. Such steam-air mixtures, however, deteriorate the rubber bags much more rapidly than steam alone.

Steam is also the heat source which is used in the continuous production of adhesively bonded paper in the manufacture of stock such as solid or corrugated fiberboard. In such cases, the steam is used to heat the large cylinders or "cans" against which a felt or canvas holds the assembly during the drying period.

### ELECTRICAL HEATING

Electrical-resistance heating elements can be used in conjunction with the platens of ordinary hydraulic presses or with forming dies when these are used for the production of laminates. Electrical-resistance heating is more expensive than steam and is usually confined to those cases where molds or die forms are involved. In such cases strip heaters are used to heat a thin-metal facing on the forms.

Another resistance heating method which is mentioned for the sake of completeness is the development of conducting glue lines. These may be in the form of either an adhesive in which a conducting material has been incorporated or resistance wires introduced directly into the glue line and bonded into the laminate. Both of these methods have been the subject of considerable experimentation, but they have never been used to any extent in production operations.

### RADIO-FREQUENCY HEATING

One of the newest methods of heating laminated assemblies, particularly wood, is with radio-frequency power also called high-frequency heating.\*

There is no essential difference between the heating of poor conductors with radio-frequency currents and the heating of metals or similar good conductors with direct or low-frequency electric currents. The use of radio frequency in heating poor conductors is merely one of practicality since the equivalent resistance of a material in an electric field drops almost inversely with the frequency of the applied current. Thus, although the applied voltage of a direct or low-frequency current would have to be extremely large in order to pass a current through such poor conductors as laminates usually are, at high frequencies of the order of radio frequencies this impressed voltage requirement is reduced to a few thousand volts, a practically obtainable and workable voltage range. The heating effect is due to the "conduction loss" which occurs as a result of the actual passage of an electric current through the material in the field. In practice, the frequencies employed range from 1 to 30 megacycles, and the voltages may vary from a few hundred volts for thin materials up to as much as 15,000 volts. Above

\* A review and bibliography are published in the proceedings of the Conference on Radio Frequency and its Applications in Gluing Wood held Jan. 16, 1947 at the College of Forestry, Univ. Wash., Seattle.

15,000 volts, corona effects become evident which make higher voltages impractical. The problems of suitable equipment and electrode design as well as the calculation of power requirements for a given installation are best left to the several equipment companies who are manufacturing radio-frequency heating equipment.

The advantages of high-frequency heating result from the fact that the heating effect is internal rather than applied from the outside of the laminate. This application of power internally allows more rapid and uniform heating than is possible with external platens or dies. It is obvious that radio-frequency heating enjoys its greatest advantage over other heating methods when thick assemblies of the order of 1 in. and larger are under consideration. Radio-frequency heating is particularly adapted to the manufacture of heavy laminated timbers, the edge gluing of lumber cores for thick plywood panel manufacture, and for the uniform heating of preform paper-base or cloth-base laminates which are to be subsequently shaped between heated dies. Radio-frequency heating should be considered in those cases where high production speeds are mandatory, where thick sections of laminate are involved, or where uniform heating during the curing period is required.

The efficient use of high-frequency heating methods depends on the proper design of the electrode assembly and also on a proper tuning of the heating circuit with the radio-frequency generator. In addition to these factors, the uniform heating of an assembly in a radio-frequency field depends on the uniformity of the electrical characteristics of the work. This limitation is of particular significance in the bonding of wooden assemblies which may vary in moisture content, density, and consequent power-factor characteristics. A study by Dunlap and Bell <sup>75</sup> of the Forest Products Laboratory is particularly worthy of consideration, since the potentially variable factors have been isolated in separate experiments.

As a broad generalization, the adhesives most suitable for radio-frequency applications are those capable of cure at ordinary room temperature. Thus, the time cycle for complete cure can be very much accelerated by the use of radio-frequency heat, and yet small variations in temperature throughout the assembly do not become significant.

#### OVEN OR KILN HEATING

Another major method of applying heat for the bonding of laminates is with circulating hot air or flue gases. Continuous laminating can be

carried out by passing the laminate through ovens, usually supported on either rollers or a combination of rollers and supporting film and heating the air space with rapidly circulating hot air. In a few very specialized cases, even direct flames may be employed in high-speed operations similar to those which are found in the flash drying of printing inks.

Kilns are usually heated with steam radiators and circulating fans, and the maximum temperature attained by the air in such kilns is approximately 200°F. This system is limited in its usefulness for ordinary laminate production but is frequently encountered in the laminating of timbers and similar wooden assemblies. Even heating in kilns is difficult, and, where wooden assemblies are involved, good control of both heat and humidity is important. In addition to heating the air, it is desirable to maintain the relative humidity at the level which will prevent the excessive drying out of the wooden assembly with resultant end checks and similar imperfections which result from the overdrying of the wooden members. The humidity in kilns for timber lamination is usually maintained automatically by introducing live steam into the heating chamber.

The penetration of heat into a laminated assembly from circulating hot air is slow, and several systems have been devised for improving this heat penetration. The most effective method<sup>76</sup> is that developed during World War II by Gamble Brothers of Louisville, Ky. This system consists of interleaving the laminates in a pile with metal cauls which act as conductors and, therefore, introduce heat by conduction between the individual laminated assemblies of a bale under pressure.

#### DETERMINATION OF CURE AND THE SETTING UP OF CURING SCHEDULES

Any discussion of the curing of thermosetting adhesives finally devolves on methods of estimating the degree of cure and the setting up of curing schedules which will cure the adhesive in question to its ultimate final state. The criteria of full cure are usually some physical properties which vary with the degree of condensation or polymerization of the adhesive. These may be the solubility of the cured adhesive in solvent, the density of the laminate as a whole, the shear strength, or the impact strength of the finished assembly. The system of establishing curing schedules for plywood has been described in considerable detail in a paper by Grinsfelder and Collins.<sup>77</sup> This general system can be applied to almost any physical property of a laminate or adhesive glue line with equal success.

## THE PROPERTIES OF BONDS

## PHYSICAL STRENGTH

The primary property of the adhesive in a composite structure which is of interest to the engineer is physical strength. A ramification of this property is the aging behavior of the glue line under the conditions of service, that is, the durability of the adhesive in relation to the other materials of construction and the changes in strength with time. The aging factors are complicated by such considerations as corrosion, temperature and humidity changes, vibration fatigue, and the type of stress in service.

The physical strength of an adhesive bond may be analyzed in terms of the deformation of the bonding material under stress. This deformation will depend on the temperature, and the amount and rate of loading. The three components of such deformation are: (a) elastic deformation, (b) highly elastic deformation, (c) viscous deformation.

A first approximation of the total deformation has been expressed mathematically by Alexandrov and Lazurkin<sup>78</sup> and modified by Simha<sup>79</sup> as follows:

$$D(t) = d_{OE} + d_{HE}(\infty) \left[ 1 - \exp. \left( -\frac{t}{\lambda} + \frac{t\gamma}{\eta} \right) \right]$$

where  $D$  = total deformation

$t$  = time elapsed between start of loading and the instant of observation, rate of loading being constant

$d_{OE}$  = ordinary elastic deformation

$$= \frac{\gamma}{G_{OE}}$$

$\gamma$  = stress

$G_{OE}$  = ordinary shear, tension or compression modulus of elasticity

$d_{HE}(\infty)$  = ultimate high elastic deformation

$$= \frac{\gamma}{G_{HE}}$$

$G_{HE}$  = modulus of high elasticity

$$\lambda = \frac{\eta_{HE}}{G_{HE}}$$

$\eta_{HE}$  = viscous effect associated with highly elastic deformation

The adhesion of the bonding material to the surface to be joined and the cohesion of the adhesive itself determine the strength of the joint.



In general, thin glue lines are stronger than thick ones beyond the lower limit of sufficient adhesive to form a continuous bonding film.

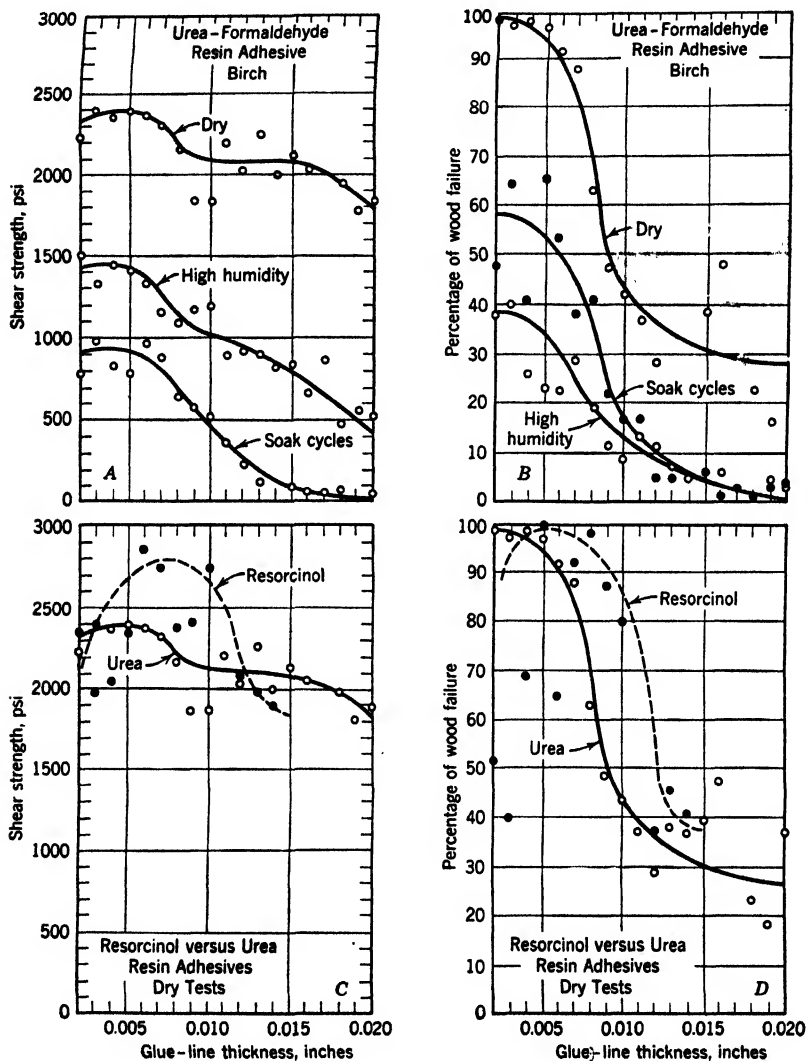


FIG. 2-7. Glue-Line Strength as a Function of Glue Thickness.

Experimental evidence of this relationship in plywood construction is given by Poletika.<sup>80</sup> Graphical representation of the results is shown in Fig. 2-7.

Similar evidence for soft-soldered joints is presented by Crowe,<sup>81</sup> who found that very thin joints yielded values several times the tensile strength of the solder.

The practical problem of joint strength is complicated by the possibility of residual stresses which may be an inherent part of the laminated system. These stresses can result from the bonding of elastically deformed laminas into a composite structure which holds the individual members in tension, but, more frequently, the residual stresses are the result of dimensional changes of the laminated members and the adhesive owing to changes in temperature, pressure, or humidity. Thus, a laminate made with a thermosetting adhesive in a hot press is bonded at elevated temperatures, under pressure, and during bonding may lose moisture. On cooling to room temperature and regaining equilibrium moisture content, different coefficients of expansion will result in internal stresses which are unrelieved. Similar changing stresses are the result of variations in atmospheric conditions from day to day.

The effect of stresses inherent in the construction, the stresses resulting from the conditions of use, and the aging characteristics of the laminas and the adhesive combine to determine the durability of the structure.

The initial strength of the joint and the strength on aging have been a subject of specialized investigation for specific cases but comparatively little work has been done on the fundamentals of the problem.

#### TESTS FOR STRENGTH OF ADHESIVES

Strength testing of adhesives is complicated by the necessity of stressing not only the adhesive but the adherend as well. Frequently the break occurs in the adherend, because it is weaker than the adhesive, and a true picture of the strength of the adhesive is not obtained.

Although glues have been used since earliest recorded times, methods of making strength tests have not been generally standardized, and it is only within the past few years that the American Society for Testing Materials, for instance, has undertaken to promulgate standard methods which might be universally accepted and employed.

Two types of test—tension and shear—are most commonly employed. Two variants of a tension test are shown in Fig. 2-8, *A* and *B*. Specimen *A* is used for metals and similar strong adherends which are not likely to fail. Specimen *B* is used for wood—side-grain glued—because the test sets up tensile stresses perpendicular to the grain of the wood, and failure is almost certain to occur in the wood unless the glued area is reduced. In both tests the tensile load may be applied either by

gripping the edges of the lips or by applying an axial load by some other means.

Specimens *A* and *B* may be employed as torsion specimens to test the shear strength of the adhesive. Although torsion tests are excellent for determining shear strength, rather specialized equipment is required, and shear tests are usually made on specimens illustrated in Fig. 2-8, *C* to *K*, inclusive.

In the wood industries, two methods of making shear tests have been widely employed. These are the "compression-shear" and "plywood-tension-shear" tests illustrated in Fig. 2-8, at *C* and *G*, respectively. The "compression-shear" or "block-shear" test generally is made with  $\frac{3}{4}$ -in.-thick northern-hard-maple blocks glued together to form an overlap 2 in. wide and  $1\frac{1}{2}$  in. long. One block is forced past the other, usually at a nominal rate of 0.015 in. per minute, until failure occurs. The usual plywood specimen, shown at *G* in Fig. 2-8, is made of three  $\frac{1}{16}$ -in.-thick veneers. The ends of the specimen are gripped, and the load is applied at the rate of 600 to 1000 lb per minute. With the same glue, these two tests give strength values that are widely different (for example, values might be 3000 psi in compression shear as compared to 400 psi in the plywood-tension-shear test). In both tests, any good wood glue causes a large proportion (70 to 95 per cent is common) of the failure to occur in the wood.

Both of the foregoing tests are open to the objection that pure shear is not obtained, that sizable tension stresses perpendicular to the glue line are set up, and that heavy stress concentrations occur at the ends of the glue lines. To overcome some of these objections in the compression-shear test, specimens *P*, *E*, and *F* are sometimes employed. In *D* the line of action of the load passes through the center of the overlap. In *E* and *F* the loading is symmetrical. None of these overcome the stress concentrations at the ends of the glue lines, and *E* and *F* are subject to the objection that the weaker of the two glue areas will fail first, thereby causing complete failure and giving strength values which are consistently low.

"Tension-shear" tests are frequently employed, particularly for non-wooden adherends such as metal and plastic laminate, although strips of birch or maple veneers are also employed for these tests. The commonest type is shown at *H* in Fig. 2-8. Although simplest to make, it is open to the objections of eccentricity and stress concentrations at the ends of the glue line. The tapered specimen shown at *I* largely overcomes the stress concentrations but is eccentric. If the tapered instead of the flat sides are brought together, both objections can to a consid-

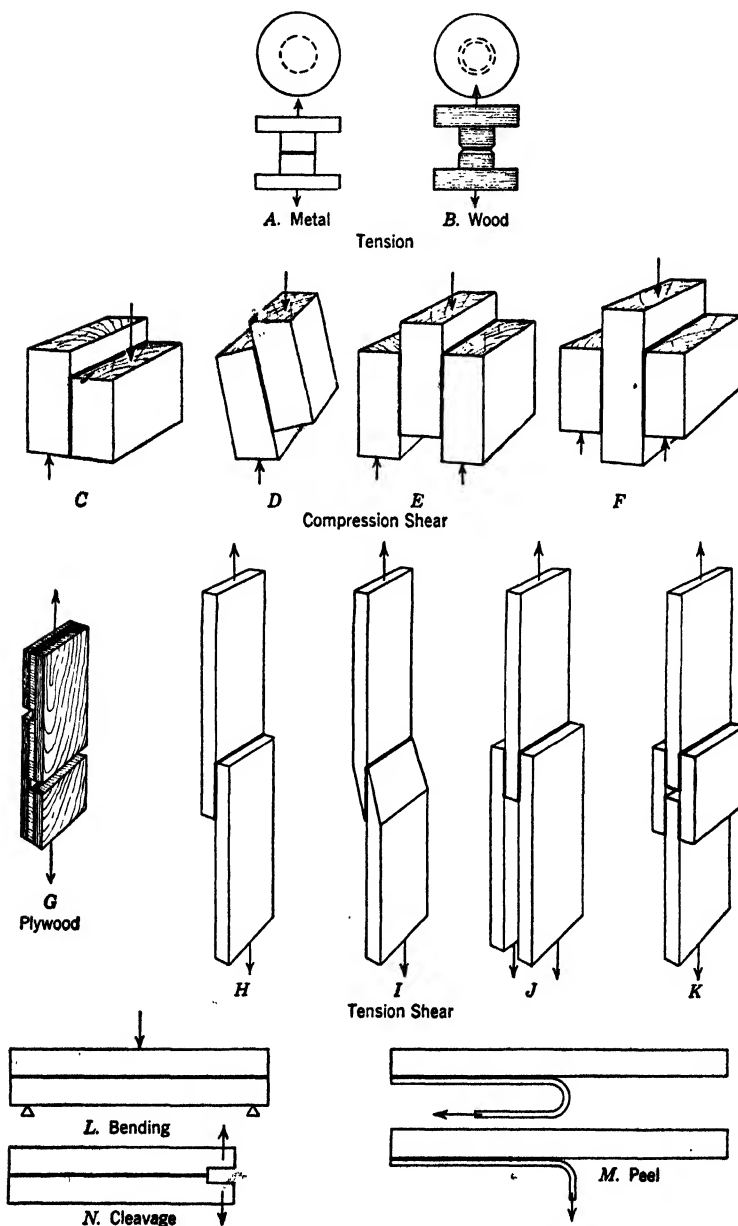


FIG. 2-8. Test Specimens for Strength Tests.

erable extent be overcome, but such a specimen is difficult to fabricate and in the case of wood necessitates a long taper to avoid an appreciable amount of end-grain gluing. The specimens shown at *J* and *K* are symmetrical but have two and four glue areas, respectively, one of which, in general, will fail before the others, thereby causing complete failure and giving strength values which are consistently low. Stress concentrations occur at the ends of the glue lines.

A bending test sometimes employed is illustrated at *L* in Fig. 2-8. The span is made short relative to the depth, so that large horizontal shear stresses are induced at the glue line. The test specimen is simple, and the test is easy to make, but the stresses in the glue line are complex and include, in addition to shear, other large stresses difficult to analyze.

Cleavage, as opposed to direct tension, is a type of stress likely to be encountered, and one type of cleavage test is shown at *N* in Fig. 2-8. The type of notch may vary with different materials, notably wood, and the position of the loads with respect to the notch is important with some relatively nonrigid materials. Loads are preferably applied directly in line with the back of the notch. Test evidence seems to indicate that the specimen can be quite short relative to the over-all thickness and that longer specimens do not appreciably increase the cleavage strength. Probably a fairly direct relationship exists between cleavage and tensile strengths.

Peel is still another strength attribute which, although related to tension, may require separate evaluation. Two methods of testing are shown at *M*, Fig. 2-8. In both, a flexible strip is bonded to a rigid material and is peeled off, in one instance parallel and in the other at right angles to the rigid material. Strength values are different for the two tests and are dependent, among other things, on the rate at which the strip is peeled.

Fatigue tests are in general far from standardized. They have generally been made on specimens similar to types *H* and *J*, by vibrating the end or the center of the specimen laterally, sometimes in pure bending, sometimes in combined bending and shear, sometimes under constant amplitude of deflection, sometimes under constant amplitude of load. Results, in general, depend on the manner in which the test is made. Whether a true fatigue limit exists in adhesives remains to be seen. One problem in fatigue testing is to avoid fatigue failures in the adherend.

Impact testing has been approached from two standpoints—tension and shear. Tension impact tests have been made with falling weights

impinging on specimens of types *A* and *B*, Fig. 2-8. The usual procedure is to allow a given weight to drop repeatedly from a given height until failure occurs. The number of blows is plotted on a graph. The test is repeated with the same weight at other heights of drop, and a curve is drawn through the points on the graph and extrapolated to find the height of drop which would just suffice to cause failure with a single blow. In a sense, this is also a fatigue test. A variant of the test is to allow the weight to fall from successively greater heights until the specimen fails.

Impact shear is carried out on a specimen similar to *C*, Fig. 2-8. The larger block is held rigidly and the small one is struck with sufficient force to carry it away, usually by a pendulum of sufficient mass swinging from a sufficient height to cause failure. The energy absorbed is measured by noting the difference between the initial height of the arc and the final height to which the pendulum has swung. The test may be varied by allowing the pendulum to impinge on the specimen from successively greater heights until failure occurs.

The testing of the physical properties of the bond between two adherends is subject to experimental variations which depend on the reproducibility of the test method, as well as on the conditions of bonding of the particular structure under consideration. For this reason, a single observation or test is almost never sufficient to define the quality or property under test quantitatively. This variation in test results is particularly significant when two adhesives are being compared for efficiency in bonding specific materials. Laboratory tests to decide between two adhesives, to control the quality of production of laminates being manufactured commercially, or to serve as a sound basis for research improvements in adhesives for laminating techniques should be considered statistically.

The statistical analysis of test results extracts from the available data the maximum amount of information and also defines mathematically the confidence to be placed in the results.

The application of statistical methods to the analysis of experimental data has made rapid strides during World War II. Outstanding publications in this field have been made under the auspices of the Ordnance Department<sup>82</sup> and also by the Statistical Research Group of Columbia University for the National Defense Research Council Committee of the Office of Scientific Research and Development.<sup>83</sup>

An excellent approach to the fundamentals of the problems of statistical presentation is given in the *ASTM Manual on Presentation of Data* published by the American Society for Testing Materials.

## THE STATISTICAL APPROACH

Since in testing work the class of data obtained is usually a set of observations of a single variable, the minimum data which should be presented are the average value, the standard deviation, and the number of observations.

Information regarding the distribution of the quality which is being tested are commonly furnished by data of this type, usually with an ulterior motive such as the establishment of a quality standard or the determination of conformance with a specified quality standard.

For approaching such data statistically, any set of observations which is to be treated as a single unit should represent a series of measurements made under essentially the same test conditions and on a bond or laminate which has been produced under essentially the same conditions.

Data gathered under different test conditions or representing a material produced under different bonding conditions should never be considered together statistically but rather as independent separate subgroups of observations and should be treated independently in the statistical analysis. Briefly stated, any set of observations which is to be analysed statistically must be *homogeneous*.

In test work where usually a single property is under consideration the problem of a statistical analysis of the data resolves itself into a consideration of the frequency distribution of a set of observations. This can be approached by considering the characteristics which are the representative measures of the frequency distribution. These are the arithmetic mean  $\bar{X}$ , the standard deviation  $\sigma$ , and the skewness factor  $k$ , all of which are algebraic functions of the observed values.

The arithmetic mean,  $\bar{X}$ , of a set of  $N$  numbers  $X_1, X_2, X_3 \cdots X_n$  is the sum of the numbers divided by  $N$ ,

$$\bar{X} = \frac{X_1 + X_2 + X_3 + \cdots + X_n}{N} \quad \text{or} \quad \bar{X} = \frac{\sum_{i=1}^{i=N} X_i}{N}$$

The term "average" is the common designation for the arithmetic mean of a set of numbers.

The standard deviation is the most useful measure of the dispersion of a frequency distribution or "population." The standard deviation \*

\* Mathematically not rigorous, strictly the most efficient estimate of the true standard deviation; usually represented by the symbol  $s$  rather than  $\sigma$ .

$\sigma$  of a set of  $N$  numbers is the square root of the average of the square of the deviations of the numbers from their average  $\bar{X}$ .

$$\sigma = \sqrt{\frac{\sum_{i=1}^N (X_i - \bar{X})^2}{N - 1}}$$

or, for practical calculations this can be simplified to

$$\sigma = \sqrt{\frac{N \sum_{i=1}^N X_i^2 - \left( \sum_{i=1}^N X_i \right)^2}{N(N - 1)}}$$

In order further to simplify calculations,  $\sigma^2$  the "variance" may be reported.

In this brief discussion of the statistical approach we will consider only "populations" which are defined completely by the arithmetic mean and the variance, that is, populations which are normally distributed around the arithmetic mean. In a normal distribution curve, 50 per cent of the results will fall within the limits of the mean value plus or minus 0.67 times the standard deviation, 5 per cent of the results will fall within the limits of the mean value plus or minus 1.96 the standard deviation  $\sigma$ , and 99.8 per cent will fall within the limits of the mean value plus or minus 3.09 $\sigma$  (sigma). The same thing can be expressed by saying 1 in 4 of a set of test results will fall below the mean value minus 0.67 sigma, or 1 in 40 below the mean value minus 1.96 sigma, whereas only 1 in 1000 is likely to be below the mean value minus 3.09 sigma. This concept is particularly useful in the writing of performance specifications.<sup>84</sup> Another way of presenting this general idea is by the establishment of so-called confidence levels or confidence intervals. Thus, the arithmetic mean and the variance will define an interval which is usually taken as either of 5 or 1 per cent and which defines the interval of results to be expected when only 5 or 1 per cent of the results, respectively, will lie outside the defined limits on a fortuitous probability basis.

In the setting of standards, the statistical approach can be quite useful when the standard of quality to be maintained, as defined in the test method, is considerably more severe than the service conditions to which the particular construction is to be subjected. In this way, the service conditions lie in the region of very few failures, and the stand-



ard to be met by the construction under test conditions is fixed so that approximately half the test specimens fail.

In this way a small number of samples can be tested which will give an indication of what can be expected of the piece in final service.

The statistical approach is probably most useful in the routine control of quality where quality-control charts can be set up which will reveal drifting changes in the quality of the product on the basis of graphical representation. Such charts will also give a measure of the significance or nonsignificance of such drifts in routine production. For the minimum amount of testing the approach is best made the basis of sequential analysis where only a sufficient number of samples are tested to determine whether a lot is acceptable or whether testing should be continued.

There are several precautions to be observed in the application of statistics in the analysis of data:

1. When the data are treated as coming from a normal population, one must be certain that the population is normally distributed.

2. The data must be homogeneous; in other words, the test conditions and the object under test must belong to the same group produced and tested under essentially the same conditions.

3. All data must be statistically independent; that is, the individual values must not depend on or be influenced by the preceding or the following value.

## STANDARDS

Below are listed some of the specification standards which are in force at the present time (1948). These include not only the commercial standards which serve as grading criteria for industrial applications but also the principal specifications by the various service departments. It must be remembered that such specifications are subject to constant revision, usually upwards, as new and improved adhesive materials become available. The reader is cautioned, therefore, to obtain the latest form of any specification which is being considered as a basis for commercial operations.

### Plywood

#### Flat

CS35-47  
CS45-47

Hardwood plywood  
Douglas fir plywood

} Obtainable from Superintendent of Documents, Government Printing Office, Washington 25, D. C.; or Division of Trade Standards, National Bureau of Standards, Washington 25, D. C.

AN-P-69	Plywood and veneer,	} Obtainable from Commanding General, Air Technical Service Command, Wright Field, Dayton, Ohio, or Bureau of Aero- nautics, Navy Department, Washington 25, D. C.
JAN-P-66	Aircraft flat panel Plywood, flat panel	

**Molded**

AN-P-43	Plywood, aircraft, molded (fluid pressure)—Obtainable from Commanding General, Air Technical Service Command, Wright Field, Dayton, Ohio, or Bureau of Aeronautics, Navy Department, Washington 25, D. C.
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**Packages and Containers**

JAN-P-105A	Packaging xx for overseas ship- ment, boxes xxx plywood	} Obtainable from Commanding General, Air Technical Service Command, Wright Field, Dayton, Ohio, or Bureau of Aeronautics, Navy Depart- ment, Washington 25, D. C.
JAN-P-112	Packaging xx for overseas ship- ment, drums, plywood	
JAN-P-139	Packaging xxx plywood container grade	
AN-P-72	Plywood; container	

**ADHESIVES****Urea for Wood**

AN-G-8	Glue; cold-setting resin—Obtainable from Commanding General, Air Technical Service Command, Wright Field, Dayton, Ohio, or Bureau of Aeronautics, Navy Department, Washington 25, D. C.
AXS-1102	Glue; urea—formaldehyde resin for cargo bodies—Obtainable from Office, Chief of Ordnance, Washington, D. C.
52-G-11	Glue; resin (urea formaldehyde)—Obtainable from Bureau of Ships or Bureau of Supplies and Accounts, Navy Department, Washington, D. C.
C-G-496	Glue; resin-type liquid and powder—Obtainable from Superintendent of Documents, Government Printing Office, Washington 25, D. C.

**Phenolic, Resorcinol, and Melamine for Wood**

14,124A	Glue; low-temperature xx (phenol, melamine, and resorcinol)—Obtainable from Office of the Commanding General in following Army Air Forces ATSC Districts: New York, Detroit, Chicago, Wichita, Los Angeles, and Warner Robins, Ga.; or from Director, Army Air Forces, Headquarters, Air Technical Service Command, Wright Field, Dayton, Ohio.
52-G-12	Glue; phenol formaldehyde, low-temperature setting—Obtainable from Bureau of Ships or Bureau of Supplies and Accounts, Navy Department, Washington, D. C.
JAN-A-397	Adhesives xxx (phenolic, resorcinol, and melamine)—Obtainable from Commanding General, Air Technical Service Command, Wright Field, Dayton, Ohio, or Bureau of Aeronautics, Navy Department, Washington 25, D. C.

- AXS-1665      Glue xxxx resorcinol base for wood vehicle parts—Obtainable from Office, Chief of Ordnance, Washington, D. C.
- G-33            Glue; phenol-aldehyde resin—Obtainable from Bureau of Aeronautics, Navy Department, Washington 25, D. C.

**Metal and Plastic Adhesives**

- |           |   |   |
|-----------|---|---|
| G-35      | Glue; metal-to-wood, sandwich construction (two-step process) | } Obtainable from Bureau of Aeronautics, Navy Department, Washington 25, D. C.  |
| G-36      | Glue; metal-to-metal nonstructural (hot press)                |   |
| G-37      | Glue; metal-to-wood, structural (hot press, one-step process) |   |
| G-38      | Glue; synthetic resin (plastic-to-plastic)                    |   |
| AAF-20032 | Metal-to-metal and metal-to-wood                              | } Obtainable from Office of the District Supervisor in following Army Air Forces Procurement Districts: New York, Atlanta, Detroit, Chicago, Wichita, and Los Angeles; or from Commanding General, Army Air Forces, Matériel Command: Wright Field, Dayton, Ohio. |
| AAF-20034 | Cementing metal-to-metal                                      |   |

**HIGH FREQUENCY HEAT APPLICATION**

- AAF-20041      Glue; curing process, h-f dielectric heating—Obtainable from Office of Commanding General in following Army Air Forces ATSC Districts: New York, Atlanta, Detroit, Chicago, Wichita, and Los Angeles; or from Director, Army Air Forces, Headquarters, Air Technical Service Command, Wright Field, Dayton, Ohio.

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## Glued-Laminated Wood

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### HISTORY

The first development of glued-laminated construction used softwoods and casein glue in Europe during the first decade of the 20th century. In 1934 at the Forest Products Laboratory, Madison, Wis., a laboratory building was constructed using glued-laminated three-hinged timber arches. These first sproutings charted the course for a multitude of like structures that today use the combination of wood and glue to increase the size and enhance the value of timber.

The tremendous demands for wood during World War II expanded the use of glued-laminated members to amounts far beyond peacetime records. During the war years glues and gluing technics were developed to resist exposure to weather, to resist repeated soakings in fresh or salt water, and to withstand pressure treatment. Glued-wood construction is now an established industry, and glued members are quickly made for ships, barges, bridges, and buildings either for indoor protected locations or for extreme exposure.

### INTRODUCTION

Laminating introduces a measure of freedom in timber design and fabrication hitherto virtually unattainable in wood. It permits the selection of material in a member to place high strength and good appearance where strength and looks are most needed and permits placement of less desirable materials in positions where they are sufficient.

Since glued members are built from dry lumber, they are not subject to the checking, splitting, warping, and twisting that occur in solid timbers erected unseasoned and permitted to season in place, nor do they require much servicing after installation. Laminated members

can be produced seasoned in a relatively short time whereas large solid timbers may require weeks or months to reach moisture stability.

Large-size and long-length timbers may be produced from narrow widths and short lengths. Thus glued members may be built to larger cross sections and longer lengths than can otherwise be produced or transported. By making big ones out of little ones one can utilize smaller and otherwise unmerchantable trees.

Glued-laminated members may often eliminate field assembly costs and permit reduction in erection costs, since arches and barn rafters require little or no assembly and wall and roof framing are erected as a unit. Laminated assemblies are especially economical of hardware and ironwork, as long-span arches often have no steel connections except anchorages at the base and splices at the crown. Glued members, such as arches and long-span girders, require far less fabrication than like-use timber trusses. Some special operational uses or manufacturing processes require freedom from iron or steel with their disturbing electrical, magnetic, or corrosive influences, and all-wood and no-steel construction is best served by glued members.

Glued construction, however, has the handicaps of high cost and restrictions of transportation. To date, laminators have been unable to produce a glued product at solid timber costs. Erroneously, the belief exists that scrap and waste can be utilized in a glued member that by some strange alchemy becomes low in cost and high in strength.

Actually, good laminated members require good lumber, generally in larger quantities than similar solid pieces. To secure a 12-in.-by-24-in. solid timber there must be purchased 24 bd ft per linear foot, but to produce a 12-in.-by-24-in. glued member there must be purchased 32 bd ft per linear foot since dressing and scarfing of laminas take a 33 per cent toll. To lumber supply, the laminator must add glue, plant, equipment, labor, and supervision to obtain a member that is only then equivalent to a mill-delivered stick. Fabrication, hardware, ironwork, transportation, assembly, and erection must later be added in like quantities to either mill-delivered or laminated timber.

Transportation clearances restrict shipment of large curved members, and so designers and laminators are restricted in large-piece shop production. Large boomerang arches are especially hard to design and build except for near-by sites. Long-distance shipping restrictions require splices near sections of maximum bending moments, which make members unsightly and cost prohibitive. Shipping restrictions account largely for the preference for three- over two-hinged arches. Field gluing is costly and awkward and often productive of inferior work.



This chapter describes the design of solid-type structural glued-laminated members for commercial use and outlines such considerations of lumber, glues, and shop assembly as directly affect such design. Neither plywood nor plywood combination members are included. Only those engineering principles which are special to glued-laminated members are considered. To save space in this chapter glued-laminated members are often termed glued members or glued arches, and the term solid is used rather than sawn solid.

## NOTATION

<i>A</i>	Cross section area in sq in.
<i>b</i>	Breadth of member in in.
<i>B</i>	Bay length or arch or truss spacing in ft.
<i>Bds</i>	Boards.
<i>bd ft</i>	Board feet.
<i>B &amp; S</i>	Beams and stringers.
<i>c</i>	Compression with grain WUS in psi.
<i>C</i>	Stress coefficients.
<i>d</i>	Depth of member in in.
<i>D</i>	Deflection in in.
<i>DL</i>	Dead load.
<i>e</i>	Eccentricity of curvature in in.
<i>E</i>	Modulus of elasticity in psi.
<i>fc</i>	Bending WUS in psi.
<i>ft</i>	Bending compression WUS in psi.
<i>f</i>	Bending tension WUS in psi.
<i>h</i>	Height in ft.
<i>H</i>	Horizontal thrust in lb.
<i>J &amp; P</i>	Joists and planks.
<i>l</i>	Span of beam in ft.
<i>L</i>	Load of psf.
<i>LL</i>	Live loads.
<i>M</i>	Bending moment in in.-lb.
<i>mph</i>	Miles per hour.
<i>pcf</i>	Lb per cu ft.
<i>plf</i>	Lb per lin ft.
<i>psf</i>	Lb per sq ft.
<i>psi</i>	Lb per sq in.
<i>P &amp; T</i>	Posts and timbers.
<i>r</i>	Radius of curvature in in.
<i>R</i>	Radius of curvature in ft.
<i>s</i>	Section modulus.
<i>S</i>	Span of arch or truss in ft.
<i>t</i>	Thickness of lamina in in.
<i>T</i>	Axial thrust in lb.
<i>V</i>	Vertical reaction in lb.
<i>w</i>	Load in plf.
<i>W</i>	Total load on member in lb.
<i>WUS</i>	Working unit stress in lb.

## MEMBER TYPES

Structural timber members may be classified under three natural groups:

1. *Laminated* is the term applied in this chapter to floors, walls, roofs, beams, truss chords, arches, and like members built of boards, joists, or planks which are held together by mechanical fastenings such as nails, spikes, bolts, dowels, drifts, or treenails. Although many persons use the term laminated to include glued-laminated, I prefer to limit it to members held together by mechanical fastenings.

2. *Glued-laminated* is the term applied to beams, girders, truss chords, arches, rafters, ship frames, or like members constructed by gluing together boards, joints, or planks as laminas. Mechanical fastenings are sometimes used in addition to glue for holding laminas together, but best practice places entire dependence on adhesives and not partial dependence on auxiliary fastenings. Only seasoned lumber can be used satisfactorily.

As contrasted with plywood,\* a glued-laminated member may be defined as an assembly of wood and glue in which the grain of all laminas is approximately parallel longitudinally. Glued members in bending may have the wide faces of laminas either parallel or perpendicular to the direction of application of load.

3. *Solid* is the term applied to all timber members neither laminated nor glued-laminated. Solid members may be single pieces of solid timbers or spaced leaf members of two or more units. This type is sometimes termed sawn solid to distinguish it clearly from a solid type of glued-laminated member.

## LUMBER TYPES

Commercial structural lumber is divided into four groups:

1. Boards, termed Bds, comprise only material less than 2 in. nominal thickness. Board grading rules apply to qualities of appearance and coverage but not to qualities of strength. Boards used as stressed sheathings or stressed coverings or for laminated or glued-laminated stock must be regraded under joist and plank grading rules.

2. *Joists and Planks*, termed J & P, comprise only material 2 in. to 4 in. nominal thickness by 4 in. nominal and up in width. Loaded on the narrow faces they are termed joists, and loaded on the wide faces they are termed planks.

\* See Chapter 4, Plywood.

3. *Posts and Timbers*, termed P & T, are timbers of approximately square cross section 4 in. by 4 in. and larger which carry column or strut loads.

4. *Beams and Stringers*, termed B & S, are timbers of approximately 5 in. by 6 in. and larger which carry beam or girder loads.

Boards, joists, and planks when seasoned are used extensively as stock for laminated and glued-laminated members; neither posts and timbers nor beams and stringers are employed for this purpose.

The present wide use of planks and joists as laminas makes current grading rules inadequate, since they no longer fit all uses. Thin boards cannot well be graded to plank requirements. Laminators of necessity grade boards primarily for appearance and effective gluing. Permissible defects in planks and joists because of position may not be equally permissible in glued members since here position in member and not position in lamina governs. There is need for new grading rules for laminating stock.

#### LUMBER SPECIES

Glued members for buildings, bridges, and like structures are almost without exception constructed of Douglas fir or yellow pine. These species are strong, durable, available, and readily glued. In barge and ship work Douglas fir, yellow pine, and white oak are used. Although material in this section for the most part applies directly only to fir, pine, and oak, other species may be used, and principles given herein, in general, apply to all commercial woods.

### DESIGN

#### ASSUMPTIONS AND LIMITATIONS

Glue lines of a glued member are assumed to be as strong and durable as the wood. Glued members are designed by the same engineering principles that are used for solid timbers. Many working unit stresses are the same for glued members as for solid timbers, but some are different. See National Design Specification<sup>1</sup> and Tables 3-2, 3-3, and 3-4. Load values of mechanical fastenings such as connectors, bolts, lags, screws, nails, and spikes are the same for glued members as for solid timbers. Improper scarfing, ineffective gluing, or insufficient stagger of end joints of any lamina prohibits such a lamina from being considered an effective structural part for bending action of cross section in that portion of the member where the defective part occurs.

When all end joints in laminas of a glued member are properly scarfed, effectively glued, and sufficiently staggered, and all edge joints are effectively glued and sufficiently staggered, the member may be considered as structurally effective for its full net cross section to resist bending action produced by loads, acting either perpendicular or parallel to wide faces of laminas.

TABLE 3-1. SERVICE CONDITION STRESS VARIATIONS

Service Condition	Bending or					Modulus of Elasticity,
	Tension with Grain, %	Comp. across Grain, %	Comp. with Grain, %	Hor. Shear %	Tension across Grain, %	
(1)	(2)	(3)	(4)	(5)	(6)	(7)
(a) Always dry	100	100	100	100	100	100
(b) Wet, quickly dried	85	70	92	100	75	100
(c) Wet and damp	70	58	78	100	65	100
(d) Always wet	100	70	100	100	70	100

Service conditions *b*, *c*, and *d* are termed "extreme service conditions."

(a) *Always dry* designates conditions variously described as continuously dry, under cover, indoor, or protected. Not exposed to weather, nor to excessive dampness, nor to high humidity, nor to contact with soil, nor to any extreme service condition.

(b) *Wet, quickly dried* designates condition variously described as occasionally wet but quickly dried, in outside locations, outdoor, not under cover, subject to wet or moist conditions at intervals but not in contact with soil.

(c) *Wet and damp* designates condition variously described as more or less continuously wet or damp, wet often and slowly dried, between high and low tide, subject to wave action, buried in soil above groundwater but not buried to a depth of 10 ft or more.

(d) *Always wet* designates condition variously described as under water, submerged, below low tide, below low water, below ground-water, or buried in soil to a depth of 10 ft or more.

When edge joints are not effectively glued or sufficiently staggered, the full cross section may not be considered structurally effective for resisting bending action produced by loads parallel to wide faces of laminas.

When the material in the center three fifths of the depth of a member in bending under loads perpendicular to wide faces of laminas is only one grade lower than that in the upper and lower fifths, the allowable unit stresses in bending of the higher grade in the outer fifths apply to the entire section.

A glued member may be considered as properly designed when material provided in each zone is adequate to resist the stresses in that zone. Standard engineering analysis is used for zone-stress determination, and allowable working unit stresses are employed for the species and grade of lumber selected.

#### SERVICE CONDITIONS

Working unit stresses of all timber members are adjusted to suit various service conditions which have different moisture content and decay hazards. The classifications of service conditions and resulting percentages of published stresses shown in Table 3-1 may be used.

Glued members, glued with waterproof glues and comprising the heartwood of a durable species, or pressure-impregnated with preservatives using approved materials and approved processes and subject to any service condition, may use tabulated working unit stresses without reduction. Glued members neither pressure-treated nor made of heartwood of durable species and used in other than "*always dry*" service conditions will use reduced stresses as shown in Table 3-1. For "*always dry*" service conditions water-resistant glues may be used, but for extreme service conditions waterproof glues are required.

#### LOAD CONDITIONS

Tests prove that the strength of timber varies with duration of load, and all stresses, except modulus of elasticity, may with safety be varied accordingly. Published stress and load tables give values for permanent loading, and, where live loads remain on a structure for a short time only, somewhat higher values are recommended. Dead loads are permanent and take permanent loading values except as permitted in combination with temporary load conditions. Recognized classes of loading and corresponding increases in stresses for timber and its fastenings are:

**(a) Permanent.** All permanent or long-time loads, live or dead. Includes all loads exceeding 3 months' duration. No increase in allowable stress and load values.

**(b) Snow, Combined.** Snow loads combined with permanent live or dead loads. Includes loads not exceeding 3 months' duration at one time. Increase allowable stress and load values 15 per cent.

**(c) Wind or Earthquake, Combined.** Wind or earthquake loads combined with permanent live or dead loads. Includes all loads not

exceeding a duration of 5 min at one time. Increase allowable stress and load values 50 per cent.

**(d) Impact Combined.** Impact loads combined with permanent live or dead loads. Increase allowable stress and load values 100 per cent.

Increases apply to all stresses except modulus of elasticity. Percentages are not cumulative, and the resulting member may not be smaller, nor may fastenings be less in number, than required for permanent loading alone. Temporary load increases and service condi-

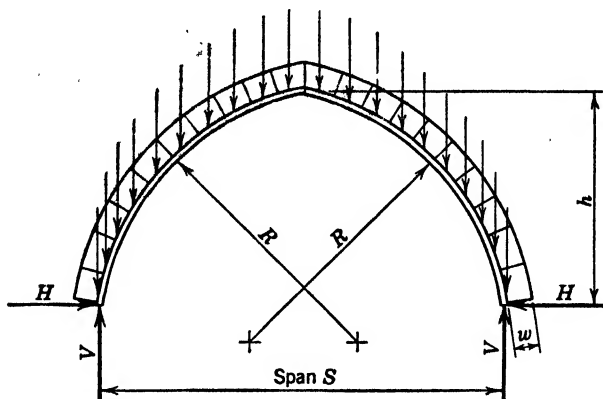


FIG. 3-1. Arch Dead Loads. Loads, thrusts, and reactions are symmetrical about center line.

tion decreases may apply to the same timber stress or fastening load value.

I know of no publication which gives loading classification for ships, boats, and barges, but it would seem reasonable to use snow-combined stresses for load, flotation, and wave action and wind combined or even impact for grounding and collision shock stresses. Load conditions of glued members are the same as those of solid timbers.

### DEAD LOADS

Dead loads are the actual weights of the structure. Dead loads for glued arches are assumed to be uniformly distributed around the perimeter of the arch, as shown in Fig. 3-1.

### SNOW LOADS

Snow loads are roof live loads and are expressed as pounds per square foot (psf) of horizontal projection of roof area. Many structures using glued members are constructed in cities where code snow-load restric-

tions govern. In nonsnow regions a minimum roof load of 20 psf should be used. In snow regions roofs are designed for live loads of 20 to 40

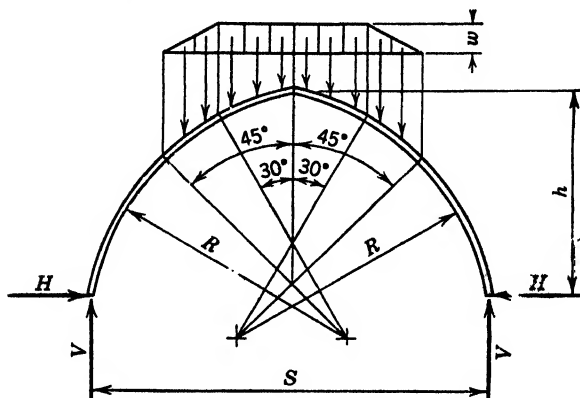


FIG. 3-2. Arch Snow Loads. Loads, thrusts, and reactions are symmetrical about center line.

psf for low-elevation sites and as much as 75 psf or more in high mountain locations.

For average low-elevation regions 6 in. of dry snow makes 1 in. of

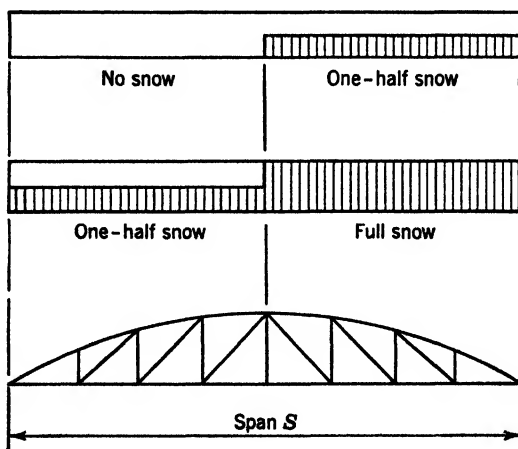


FIG. 3-3. Unbalanced Load Condition, Bowstring Truss or Low Rise Arch. Either type of unbalancing may be used as both give same result.

water, and for high-elevation regions ratios may be 10 to 1 or even 14 to 1. Dry snow varies from 8 to 10 pounds per cubic foot (pcf), and wet snow from 10 to 12 pcf. The United States Department of

Commerce issues a map giving probable snow loads in pounds per square foot for all regions of the United States.

Steep pitched and curved roofs retain less snow than flat roofs, are not subject to overflow from clogged drains, and can safely be designed for lighter loading. For curved roofs accepted practice takes snow load as full to a point  $30^\circ$  from the vertical and then reduces the load uniformly to zero at a point  $45^\circ$  from the vertical (see Fig. 3-2).

Bowstring trusses and tied arch ribs are generally designed for full snow load over the entire span and for an unbalanced condition with one-half snow load on a half-span only (see Fig. 3-3). For high curved roofs, the design is carried out for full snow load, as shown in Fig. 3-3, but the unbalanced snow load is not considered, since wind load is critical for unbalanced conditions.

Since glued members are used so extensively for curved roofs, the snow load for such types is extremely important. Combined snow and dead-load working stresses, of course, are employed in their design.

#### WIND LOADS

Standard practice and prevailing codes require structures to resist wind pressures of 10 to 30 psf. High values are used in tornado and

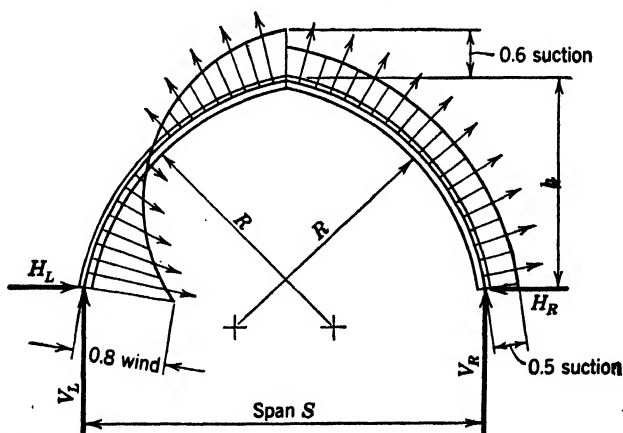


FIG. 3-4. Arch Wind Loads. Forces produced with wind perpendicular to side and all doors closed.

hurricane regions and for high buildings, whereas low values are used in normal wind regions and for low buildings. Wind and dead-load combined working stresses are employed, and both leeward and windward columns of a bent are designed to resist wind forces.



Curved bowstring truss roofs and round, gothic, mansard, and spandrel arch roofs have variable pressures and suctions. The Kansas State College Experimental Station has issued a practical bulletin on wind loads on curved roof surfaces<sup>12</sup> (see Fig. 3-4).

A complete analysis of wind pressures on buildings is found in the *Transactions of the American Society of Civil Engineers*, volume 105, page 1713, Final Report on Wind Forces on Roofs and Walls of Ordinary Buildings.

### WORKING UNIT STRESSES

Tables 3-2, 3-3, and 3-4 give allowable working unit stresses for joist and plank grades of fir, pine, and oak, for use in the design of glued members.

TABLE 3-2. DOUGLAS FIR WORKING UNIT STRESSES

Grade (1)	Bending (2)	Comp. across Grain (3)	Tension with Grain (4)	Comp. with Grain (5)	Hor. Shear (6)	Tension across Grain (7)	Modulus Elasticity (8)
<i>A. Paragraph 301—Close Grain Clears—Grain Slope 1 in 16</i>							
(a) Permanent loads	2,400	415	2,400	2,125	145	60	1,800,000
(b) Snow combined loads	2,750	475	2,750	2,450	165	70	1,800,000
(c) Wind or earthquake	3,600	625	3,600	3,200	220	90	1,800,000
<i>B. Paragraph 201—J &amp; P—Dense Select Structural</i>							
(a) Permanent loads	2,150	455	2,325	2,325	170	54	1,800,000
(b) Snow combined loads	2,475	525	2,675	2,675	195	60	1,800,000
(c) Wind or earthquake	3,225	685	3,475	3,475	255	80	1,800,000
<i>C. Paragraph 202—J &amp; P—Select Structural</i>							
(a) Permanent loads	1,900	415	2,125	2,125	145	48	1,800,000
(b) Snow combined loads	2,175	475	2,450	2,450	165	55	1,800,000
(c) Wind or earthquake	2,850	625	3,200	3,200	220	75	1,800,000
<i>D. Paragraph 203—J &amp; P—Dense—No. 1</i>							
(a) Permanent loads	1,700	455	2,325	1,975	170	42	1,800,000
(b) Snow combined loads	1,950	525	2,675	2,275	195	50	1,800,000
(c) Wind or earthquake	2,550	685	3,475	2,975	255	65	1,800,000
<i>E. Paragraph 204—J &amp; P—No. 1</i>							
(a) Permanent loads	1,450	390	2,125	1,800	145	36	1,800,000
(b) Snow combined loads	1,675	450	2,450	2,075	165	40	1,800,000
(c) Wind or earthquake	2,175	585	3,200	2,700	220	55	1,800,000
<i>F. Paragraph 205—J &amp; P—No. 2</i>							
(a) Permanent loads	1,100	390	1,650	1,625	145	30	1,800,000
(b) Snow combined loads	1,275	450	1,900	1,875	165	35	1,800,000
(c) Wind or earthquake	1,650	585	2,475	2,450	220	45	1,800,000

Values for various loading conditions are given for Douglas fir, but to save space only permanent load values for pine and oak are given. The same percentage increases for snow combined and wind and earthquake combined loading conditions are used for pine and oak as for fir,

where pertinent reductions are made in working unit stresses for extreme service conditions and for form factors.

TABLE 3-3. YELLOW PINE WORKING UNIT STRESSES

Grade (1)	Bending (2)	Comp. across Grain (3)	Tension with Grain (4)	Comp. with Grain (5)	Hor. Shear (6)	Tension across Grain (7)	Modulus Elasticity (8)
<i>Longleaf</i>							
(A) Select Structural	2,400	455	2,400	2,325	205	60	1,800,000
(B) Prime Structural	2,150	455	2,325	2,325	205	54	1,800,000
(C) Merchantable	1,900	455	2,325	2,175	205	48	1,800,000
(D) Structural—SE & S	1,900	455	2,325	2,175	205	48	1,800,000
(E) No. 1 Structural	1,700	455	2,325	1,800	205	42	1,800,000
(F) No. 1 Dimension	1,700	455	2,325	1,800	205	42	1,800,000
(G) No. 2 Dimension	1,250	455	1,875	1,550	205	32	1,800,000
<i>Shortleaf</i>							
(A) Select Structural	2,400	455	2,000	2,000	175	60	1,800,000
(B) Structural	2,150	455	2,000	2,000	175	54	1,800,000
(C) Structural—SE & E	1,900	455	2,000	2,000	175	48	1,800,000
(D) No. 1 Structural	1,700	455	2,000	1,800	175	42	1,800,000
(E) No. 1 Dense DIMEN.	1,700	455	2,325	1,800	205	42	1,800,000
(F) No. 1 Dimension	1,450	390	2,000	1,600	175	36	1,800,000
(G) No. 2 Dimension	1,250	455	2,000	1,550	175	32	1,800,000
(H) No. 2 MG Dimension	1,100	390	2,000	1,300	175	28	1,800,000

Values shown are the latest and best-established practice. Further research may change these values, but it is believed that changes will be minor, applying to selection and refinements of use, rather than radical increases or reductions in value.

TABLE 3-4. WHITE OAK WORKING UNIT STRESSES

Grade (1)	Bending (2)	Comp. across Grain (3)	Tension with Grain (4)	Comp. with Grain (5)	Hor. Shear (6)	Tension across Grain (7)	Modulus Elasticity (8)
(A) 2150 f grade	2,150	600	1,800	1,800	200	85	1,800,000
(B) 1900 f grade	1,900	600	1,800	1,800	200	75	1,800,000
(C) 1700 f grade	1,700	600	1,800	1,800	200	70	1,800,000
(D) 1450 f grade	1,450	600	1,800	1,575	200	60	1,800,000

*Bending Stresses.* Loads on a beam produce a bending moment, and the beam must set up an equal and opposite resisting moment. Bending moment produces tension on one side of the beam and compression on the other. Stress in the tension flange acts about the stress in the compression flange as a couple to form a resisting moment. The lever arm of the couple is the distance between the resultant tension and compression forces.

Flange strengths are cross-sectional areas times unit stresses. The lever arm is measured between the true centers of gravity of the strengths of the flanges. Laws of geometry and algebra are followed

in moment and stress analysis. Thus we have a compression-resisting moment and an equal tension-resisting moment. Stresses in the wood fibers vary uniformly from a maximum at an extreme fiber to zero at the neutral axis, as illustrated in Fig. 3-5B.

TABLE 3-5. ZONE STRENGTH VALUES

Zone	Maximum Stress	Average Stress	Strength, lb	Lever Arm, in.	Moment, in.-lb	Moment, per cent
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	$1.0f$	$0.90f$	$0.09fbd$	$0.9d$	$0.081fbd^2$	50.0
2	$0.8f$	$0.70f$	$0.07fbd$	$0.7d$	$0.049fbd^2$	30.0
3	$0.6f$	$0.50f$	$0.05fbd$	$0.5d$	$0.025fbd^2$	15.0
4	$0.4f$	$0.30f$	$0.03fbd$	$0.3d$	$0.009fbd^2$	4.5
5	$0.2f$	$0.10f$	$0.01fbd$	$0.1d$	$0.001fbd^2$	0.5

Column (2) Values in the maximum stress column are values of maximum possible stresses, either tension or compression, in individual zones compared with the maximum allowable working stress. These values are illustrated graphically in Fig. 3-5C. Values in individual zones for various allowable working stresses are given in Table 3-6.

(3) Values in average stress column are ratios of average stress either tension or compression in individual zones, as compared to maximum allowable working stresses.

(4) Values in strength column are total strength of each zone in pounds. Values are products of average stress values column (3) and area  $bd/10$  of each zone. Values may be either tension or compression. Zone strengths are illustrated graphically in Fig. 3-5D.

(5) Values in lever arm column are length of lever arm of individual zones expressed in terms of beam depth. In beam resisting-moment action each zone on the compression side acts as a couple about the equal-in-strength zone on the tension side. Values here are taken from center to center of zones which is not quite true, but the error introduced is small and unimportant. Lever arms are shown graphically in Fig. 3-5D.

(6) Values in moment column are respective resisting moments of the zones and a true measure of the work performed by each zone in resisting the beam bending moment and, hence, in carrying beam loads. Values are products of zone strength column (4) and lever arm column (5) and are expressed in inch-pounds. Values may be either tension- or compression-resisting moments. These values add up to a total of  $0.165fbd^2$  where the true total resisting moment of any beam is known as the product of  $f$  and the section modulus or  $fbd^2/6$  or  $0.166fbd^2$ . The slight discrepancy is a carry-over from not quite true lever-arm values. These values are illustrated graphically in Fig. 3-5E.

(7) Values in moment per cent column are percentages of the total resisting moment, either tension or compression, carried by the respective zones. Note that the outer zone carries 50 per cent of the load and that zone 5 which lies adjacent to the neutral axis carries only 0.5 per cent of the load. Outer laminas are all important, and central laminas are comparatively ineffective.

Positive moments produce compression in the top half of a beam and tension in the bottom half, whereas negative moments produce tension in the top and compression in the bottom. For convenience, a glued beam is considered as being divided into ten equal zones as illustrated in Fig. 3-5A.

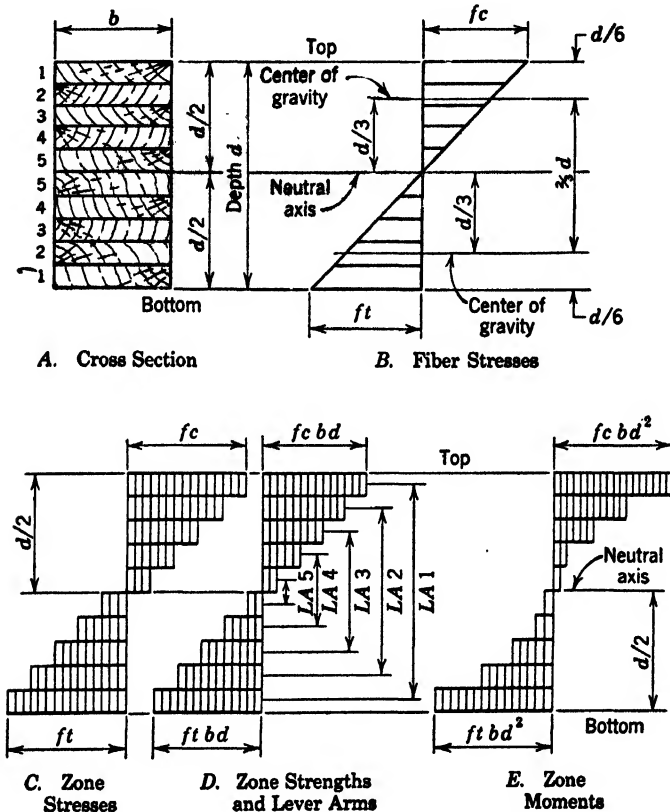


Fig. 3-5. Stresses and Zones in Laminated Beams.

In Table 3-6 working-unit-stress values in column 2 are allowable working unit stresses in bending tension or bending compression for various grades of fir, pine, or oak. They are values designated by notations  $f_c$  and  $f_t$ . Percentages and stress values given are the maximum that can occur in individual zones without allowable working unit stresses being exceeded. Values in zone 1 are identical with values in column 2 since here values are 100 per cent.

In a glued beam we may vary the cross section instead of grades and thus keep bending stresses constant. Percentage stress-variation values

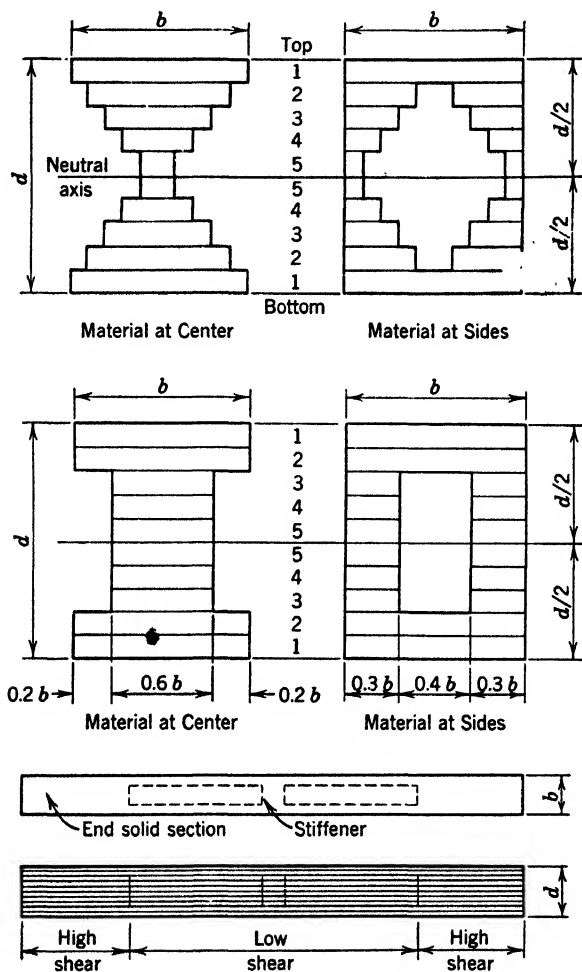


FIG. 3-6. Top, Cross Sections Showing Possible Girder Shapes Which Are as Strong in Bending as Solid Shapes. Center, Constant-Stress Beam Sections. Bottom, Longitudinal Views of Economy Shapes.

given in Table 3-6 may also be used as area variations for constant stress in all zones. Constant-stress cross sections with material at the center of the beam and at the sides of the beam are illustrated in Fig. 3-6. Other shapes more economical of wood than solid timbers are also

shown. As we consider the length of a beam, we find that maximum zone stresses as explained really occur at only certain critical points of maximum moments and then reduce to zero at supports or inflection points.

TABLE 3-6. MAXIMUM WORKING STRESSES FOR VARIOUS ZONES

	Working Unit Stress, psi	Zone One, psi	Zone Two, psi	Zone Three, psi	Zone Four, psi	Zone Five, psi
(1)	(2)	(3)	(4)	(5)	(6)	(7)
		100%	80%	60%	40%	20%
(a)	2400	2400	1920	1440	960	480
(b)	2150	2150	1720	1290	860	430
(c)	1900	1900	1520	1140	760	380
(d)	1700	1700	1360	1020	680	340
(e)	1450	1450	1160	870	580	290
(f)	1250	1250	1000	750	500	250
(g)	1100	1100	880	660	440	220

In continuous beams the stresses in laminas change from compression to tension and from tension to compression as one goes along the beam and changes signs of moments. Figure 3-7 illustrates high-stress portions in length. Other areas may be low- or zero-stress sections. Change of stress in length as well as in cross section may be taken into account in allocating material, scarfs, or defects. Bending stresses are applied in the design of glued members in the same manner as in solid timbers, and stress values for species and grade are the same for both.

#### COMPRESSION ACROSS GRAIN

Compression across grain stresses are used for connection design but seldom for design of members. Such stresses are the same for glued members as for solid members. In glued members, where construction warrants, high-compression stress species can be placed where needed.

#### TENSION WITH GRAIN

Since in glued members lumber defects which cause strength reductions are limited in extent to one lamina in depth and for arrangement are dispersed along the member, a very low-strength ratio reduction may be taken for tension-with-grain or compression-with-grain stresses which are considered as uniformly distributed over the cross section of the members.

These increases give a great advantage to glued members in comparison with solid timbers for columns, arches, and truss chords, where axial tension or compression is the major action. The greatest strength advantage of glued members compared with solid timbers lies in axially loaded members. Tension with grain unit stresses may be taken as 50

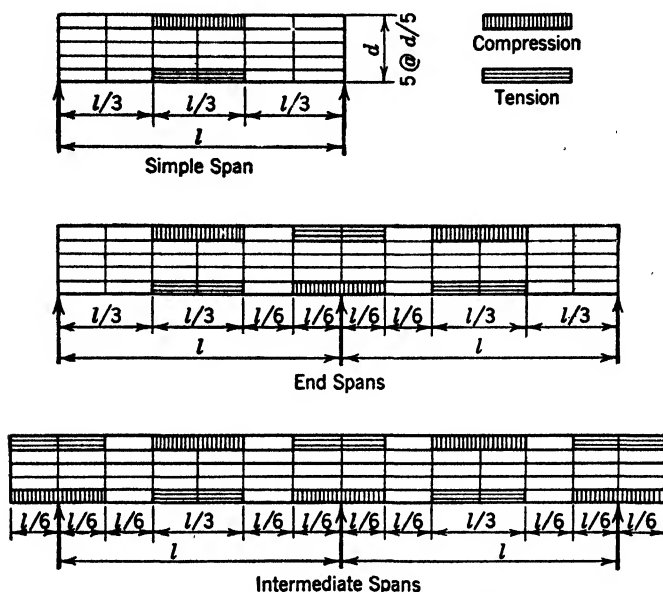


FIG. 3-7. High-Stress Portions of Beams.

per cent greater than bending stresses but not to exceed 90 per cent of basic unit stress.

Table 3-7 gives basic unit stresses for fir, pine, and oak. These values are for dry lumber whose moisture content does not exceed 16 per cent. Stress values are for permanent loading and have been adjusted for a factor of safety but not for a strength ratio. Values for other commercial woods may be found in National Design Specifications.<sup>4</sup> Tension with grain-stress values for glued-laminated members is higher than for solid timbers of the same grade and species. Grade selection has no merit where members are stressed principally in tension with grain. If grades are varied, tension stresses must also be varied to suit. Net sections are considered for computations of tension stresses. Net sections in connector joints are described in the *Teco Manual*<sup>3</sup> and in "Bolted Joints of Douglas Fir."

## COMPRESSION WITH GRAIN

For reasons given under "Tension with Grain," compression-with-grain working-unit-stress values may be 50 per cent higher for glued members than for solid timbers but may not exceed 90 per cent of basic unit stress. Zone grade selection has no advantage where the principal action is compression with grain. If grades in a member are varied, stresses must be varied to suit. Increased working-unit-stress values for compression with grain are permissible for bearing under metal plates.<sup>1</sup>

## HORIZONTAL SHEAR

Extensive tests indicate that the horizontal-shear strength of glued members is different from that found in solid timbers. This difference seems to be greater for third-point loading than for quarter-point or uniform loading.

TABLE 3-7. BASIC UNIT STRESSES

Species (1)	Unit Stresses, psi (2)
(a) Douglas fir—dense	2575
(b) Douglas fir—coast region—close grained	2350
(c) Douglas fir—coast region	2200
(d) Douglas fir—inland region—close grained	2225
(e) Douglas fir—inland region	2075
(f) Oak—white	2000
(g) Pine—southern longleaf	2575
(h) Pine—southern shortleaf—dense	2575
(i) Pine—southern shortleaf	2200

Recent tests gave for ultimate strength an average of 472 psi with a low of 431 psi. Shear strength may be higher under actual uniform loading, and certainly glued beams in service have a better shear setup than seasoned solid beams which often have wide-open spaces along the neutral axis. Possibly planers damage surfaces of laminas and lower their shear strength.

Table 25 in National Design Specifications<sup>1</sup> gives glued-laminated-member shear values for all commercial species. It is to be noted that National Design Specifications<sup>1</sup> permit 50 per cent higher shear stresses in joint details than in member design.

The Forest Products Laboratory is continuing tests on horizontal-shear stresses in glued members.



## TENSION ACROSS GRAIN

Tension across grain is sometimes used in joint design but seldom if ever in design of members. Fastening load values and their spacings as given in the tables have safe tension-across-grain conditions, and here the unit stress need not be investigated.

Since the checking and splitting so often present in solid timbers weaken them in tension across the grain, glued members have better across-grain resistance. Also glued-laminated members change grain slope at short intervals and so limit checks and splits to restricted areas. Tension across grain should be about  $2\frac{1}{2}$  per cent for softwoods and about 4 per cent for hardwoods, as compared to bending stress. Working-unit-stress values may be taken as the same for glued members as for solid timbers.

## MODULUS OF ELASTICITY

Modulus of elasticity is a measure of the stiffness and deflection of wood members and is a property rather than a stress. Dry wood has a higher value than unseasoned wood, and only dry lumber can be used in glued members. *Strength and Related Properties of Wood*<sup>9</sup> gives values for the modulus of elasticity  $E$  as set forth in Table 3-8.

TABLE 3-8. MODULUS OF ELASTICITY

Species (1)	Unseasoned, psi (2)	Dry, psi (3)
(a) Douglas fir	1,600,000	2,200,000
(b) Southern yellow pine	1,600,000	2,200,000
(c) White oak	1,200,000	1,800,000

A recent extensive test program on glued beams gave a low of 2,040,000 and an average of 2,200,000 psi. Glued beams tested in the laboratory and deflections measured in beams in service give an  $E$  of 2,150,000 psi and above. Since  $E$  does not vary with strength ratios, it is unnecessary to use the higher grades where stiffness is critical. Often, where for certain grades the design shows deflection to be critical, a lower grade may well be used and the same-size member retained.

Percentage increases in allowable stresses for temporary loading operate to make deflection more often critical, whereas percentage decreases for service conditions operate to make deflection less often critical. A higher  $E$  can be used for glued members than for solid.

## MISCELLANEOUS STRESS TYPES

Such stress types as hardness, vertical shear, cleavage, and crushing of wood are not structurally critical in either glued members or solid timbers.

## CURVED MEMBER STRESSES

For the curved portion of a glued member, the allowable working unit stress in bending is modified by multiplication by the following curvature factor:

$$1 - 2000 (t/r)^2$$

$t/r$  should not exceed  $\frac{1}{100}$ . No curvature factor is applied to stress in the straight portion of a member, regardless of curvature elsewhere.

In members curved to a radius less than 250 times the thickness of a lamina, scarfed joints are required in that portion of the member stressed 60 per cent or more of the allowable working stress. For portions of a member in which the laminas are curved to a radius of less than 150 times their thickness, the slope of the grain in those laminas within one-tenth the depth of the assembly from the outer face should not be steeper than 1 to 15.

## CURVED TRUSS CHORDS

Curved truss chords are continuous members subject to combined axial thrust (or tension) and bending actions. Truss action produces axial thrust ( $T$ ) along the top chord which tends to act along a straight line between panel points but is forced to follow the curved shape of the chord.

Transfer of normal thrust from a straight line to a curve produces a bending moment equal to thrust times eccentricity or  $Te$ . Since the top chord is a constant-section continuous member, we may say that the positive moment at panel points is  $Te/2$ , and the negative moment at mid-panel is  $Te/2$ .

Where roof loading by virtue of sheathing or joists produces a uniform load on a chord, we have a beam-active negative moment at panel points and a beam-active positive moment at mid-panel. Such moments are compensating to the eccentric moments produced by curvature. Such compensation remains in the same comparison ratio for all variations of live load from zero to maximum since live-load variations have like effect on both roof load and eccentric moment.

Where roof loading by virtue of purlins at panel points or built-up roof construction does not produce loads on the chords, the eccentric

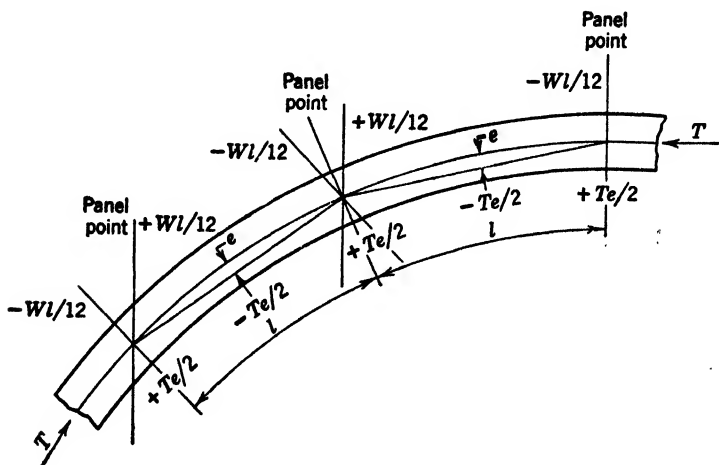


FIG. 3-8. Curved Truss Chord.

moment is uncompensated. Chords are designed for the parallel compression and bending stress combinations actually encountered (see Fig. 3-8).

### LUMBER

#### MOISTURE CONTENT

Moisture content of timber is expressed as the percentage of the weight of contained water to the oven-dry weight of the wood.

At the time of gluing the lumber should be conditioned to a moisture content of not less than 7 per cent nor more than 16 per cent and should be as close as practicable to the moisture content the member will attain in service. In general, it is desirable to produce the member at a slightly lower moisture content than later moisture stability to avoid surface rechecking. Doubtless, ideal moisture contents would be 8 to 12 per cent in members intended for indoor service and 12 to 16 per cent in members intended for outdoor service.

The uniformity of moisture content between the different laminas of any member and throughout each board is also important. If adjacent laminas differ widely in moisture content at the time of gluing, subsequent moisture-content equalization will cause them to swell or shrink

unequally and produce high glue-line stresses, possible delamination, and possible member distortion. A range of moisture content of not more than 5 per cent between different laminas of a single member is recommended. To avoid excessive internal stresses in a lamina it is recommended that the moisture-content range between the outside and the core of a single board not exceed 5 per cent.

Lumber may be either air-dried or kiln-dried. Kiln drying permits better control of humidity and final dryness, but either process is satisfactory. Moisture content can be determined either by electric meters or by oven drying. Meters are more convenient and more rapid but do not give such accurate results. Meters do not work well on treated wood.

#### NONSTRESS GRADE LUMBER

For residences and other types of small buildings much lumber is used which does not meet grading and dressing rules for assigned stress grades. Such lumber termed "nonstress" has a high stiffness quality but may have cross grain, large knots, wane, pitch pockets, wide grain, and poor appearance. Large knots, pitch pockets, and cross grain do not glue well, and poor appearance detracts from the value of any timber product.

The center zone comprising two-fifths depth of any glued-laminated beam has such low bending stress that doubtless any stress- or non-stress-grade lumber can qualify for strength. We might then say that any lumber with good appearance and with only small or medium-size knots that glues well could be used for the center two fifths for depth of a member stressed principally in bending. Since grain and density may vary widely, low grades are less adapted to glued members subject to outdoor exposure where moisture-content change may be high than to members in protected locations where moisture-content change is minimum.

#### MIXED SPECIES

With proper gluing technique various species of softwoods or hardwoods or both a softwood and a hardwood may without detriment be used in the same glued member. Also, plywood and boards or plywood and planks may be combined in the same member, but only exterior plywood should be used in members subject to extreme service conditions. In plywood combinations, boards or planks should be within 5 per cent of the moisture content of the plywood.

## MIXED GRADES

Different grades of the same species may often be used to great advantage in the same glued member. (See sections "Dense versus Nondense" and "Design Assumptions.")

## DENSE VERSUS NONDENSE

Some publications restrict the lumber in any individual glued member to either dense or nondense (yellow pine and Douglas fir) and prohibit the use of both together in arranging grade groups to suit zone stresses. Present opinion no longer requires dense and nondense selection in laminas of a glued member.

## FLAT VERSUS VERTICAL GRAIN

Some publications restrict the lumber in any individual glued member to either vertical or flat grain and prohibit the use of both together. Such requirements were based on different amounts of expansion and contraction of vertical and flat grain under moisture-content change. If different laminas change size in relation to each other, high stresses are produced in the glue lines.

Indoors, always-dry glued members have little or no moisture-content change, and here vertical and flat-grain selection is not pertinent, and laminas may without detriment be both vertical and flat grain. Outdoors, under extreme service condition exposures, glued members may have wide changes of moisture content; here grain selection is pertinent, and for such use any individual member should have all laminas either vertical grain or flat grain.

## DURABLE VERSUS NONDURABLE WOODS

Durability of wood, meaning quality of permanence, expresses the resistance to decay under conditions which favor decay. The natural decay resistance of commercial woods lies in the heartwood. Sapwood of any species has low decay resistance and short life under extreme service conditions. Comparisons of the relative decay resistance of various species cannot be exact but are approximate averages only. The following classification divides commercial woods into generally accepted groupings of durability of heartwood.

*(a) Durable under conditions which favor decay:*

- |               |              |
|---------------|--------------|
| (1) Cedar.    | (4) Redwood. |
| (2) Chestnut. | (5) Walnut.  |
| (3) Cypress.  | (6) Yew.     |

*(b) Intermediate durability closely approximating durable species:*

- (1) Douglas fir (dense).
- (2) White oak.
- (3) Southern yellow pine (dense).

*(c) Intermediate durability:*

- (1) Douglas fir (unselected).
- (2) Western larch.
- (3) Southern yellow pine (unselected).
- (4) Tamarack.

*(d) Low-intermediate durability:*

- |              |              |
|--------------|--------------|
| (1) Ash      | (5) Hickory. |
| (2) Beech.   | (6) Maple.   |
| (3) Birch.   | (7) Red oak. |
| (4) Hemlock. | (8) Spruce.  |

*(e) Low durability:*

- |                 |                |
|-----------------|----------------|
| (1) Aspen.      | (4) White fir. |
| (2) Basswood.   | (5) Willow.    |
| (3) Cottonwood. |                |

## HEARTWOOD VERSUS SAPWOOD

Sapwood is as durable as heartwood under "always dry" service conditions, but, when used where moisture content will exceed 20 per cent, sapwood of either durable or nondurable species is subject to rapid attack by fungi. Glued members subject to extreme service conditions should be pressure-treated with preservatives, but, if this is not possible, then heartwood of a durable species should be used throughout, and no sapwood should be included.

## EFFECT OF DEFECTS

Defects affect strength, pliability, and gluability of lumber.

In commercial work it is economically impossible to follow any elaborate program of charting and evaluating defects for all the ranges and combinations that occur, although some general selection and segregation can be performed, and above-average defects can be positioned in areas of low stress. Cross-cutting and ripping operations may be used to upgrade stock and to eliminate the effect of serious defects.

Defects seriously affect the bending of lumber, and any stock destined for sharp bends must be fairly clear material. Defects affect gluability, and large knots, wane, bark, and chipped grain do not glue well.

Some simple method of defect positioning in the shop must be devised. At present most laminators confine defect selection to that performed for grade selection. Often, however, the best boards and the best edges are put on the outside for better strength and better appearance.

### CONSTRUCTION DETAILS

#### LAMINA THICKNESS

No lamina in a glued member should be thicker than 2 in. net. Cost rises rapidly as thickness decreases, and, hence, in commercial work laminas are kept as thick as conditions permit. In straight members  $1\frac{5}{8}$ -in. net planks are suitable, most economical, and most often used. Curved members often require inch-thick or even thinner boards.

TABLE 3-9. MINIMUM BENDING RADII IN INCHES

	Thickness of Lamina, in.	Douglas Fir	Southern Yellow Pine	White Oak
	(1)	(2)	(3)	(4)
(a)	$\frac{1}{4}$	31	25	18
(b)	$\frac{5}{16}$	41	31	24
(c)	$\frac{3}{8}$	51	37	30
(d)	$\frac{7}{16}$	63	43	36
(e)	$\frac{1}{2}$	74	50	43
(f)	$\frac{5}{8}$	98	63	58
(g)	$\frac{3}{4}$	125	78	73
(h)	$1\frac{1}{16}$	137	82	79
(i)	1	176	100	95
(j)	$1\frac{1}{4}$	230	125	120
(k)	$1\frac{1}{2}$	290	150	145
(l)	$1\frac{5}{8}$	325	164	160
(m)	2	410	200	190

Thickness of laminas in curved members or curved portions of members should not exceed  $R/100$  (see Table 3-9). Planks and boards of varying thickness may be used in the same member to attain certain exact member depths with commercial stock.

It is extremely difficult to use thin laminas in curved portions and thick laminas in straight portions of the same member, since a good

junction between thick and thin is virtually impossible to attain. Sharp bends govern lamina thicknesses throughout the member and so increase costs greatly.

Laminas may be tapered in thicknesses to suit varying depths of members. With special machines such methods may not be too difficult nor prohibitive in cost.

Where the depth of a member varies and lamina thicknesses remain constant, it is possible to make a finish saw cut diagonally across the laminas which leaves tapered ends that are unsightly but are usually concealed by roof construction. If desired for appearance, cap plates may be installed to cover tapered ends.

### BENDING OF LUMBER

Lumber for a curved member must bend without breaking when dry, unheated, and covered with glue. Impregnation or steaming processes to increase pliability are impracticable. The minimum radius to which dry clear straight-grained untreated lumber can be bent without injury is variable for different species but is, in general, 40 to 60 times its thickness. Most hardwoods can be bent to lesser radii than softwoods.

Knots, cross grain, and other defects in lumber decrease pliability and increase the limit of safe bending radius. Best practice limits the radius of bends in commercial work to 1.6 times the breaking radius. Table 3-9 gives recommended minimum bending radii in inches for various thicknesses of fir, pine, and oak.

### BUTT JOINTS

Butt joints (Fig. 3-9) are the simplest and least costly type of lamina end connection but also the least desirable. A butt joint cannot transfer stress from one lamina to another even in struts or columns. Strange though it may seem, no laminator has yet been able to devise a means of holding contact throughout the period of pressure application.

Outer laminas with butt joints on girders are worse than no laminas, since butt joints concentrate stresses and produce critical sections. If butt joints are used, the cross section should be increased accordingly, or joints should be positioned in low-stress areas. Butt joints are not used in outer laminas on first-class work.



## PLAIN SCARFS

Plain scarfs (Fig. 3-9) being simple and effective have extensive use. Strength increases with length, but so also does the stock required to form the scarf, and a compromise must be selected that gives adequate strength at moderate cost. Authorities favor a slope of 1 to 12 which gives a scarf strength up to 80 per cent of full section.

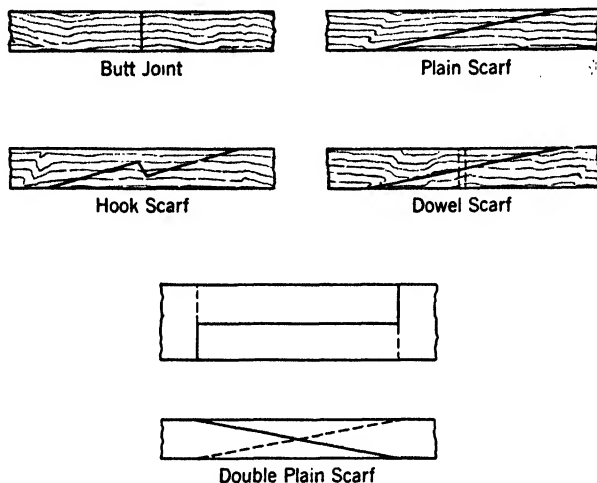


FIG. 3-9. Lamina-Joint Types.

Slope of scarf should be with and not against the grain. There is no strength advantage in having a slope of scarf less steep than the slope of grain permitted in the grade used. It is unnecessary to make a scarf slope flatter than 1 to 12 except as may be required for curved portions, nor should the slope ever be steeper than 1 to 8.

Some laminators use a double reversed plain scarf (Fig. 3-9) which gives better alignment since it has some lateral positioning action.

## HOOK SCARFS

Laminators devised hook scarfs (Fig. 3-9) to position lamina ends and avoid injurious overlap ride-up. Since bevel cuts on hook scarfs are steeper than the cuts used on plain scarfs, some strength is sacrificed. The hook does provide some additional strength but does not fully compensate for slope loss nor provide plain scarf equality.

Hook scarfs have given good service on many important projects,

but late practice has swung back to plain scarfs. Hook scarfs are, however, far superior to butt joints.

## DOWEL SCARFS

Some laminators now use dowel scarfs (Fig. 3-9) which effectively position lamina ends during assembly. The ends of two laminas on which plain scarfs have already been cut are dry-assembled and carefully positioned, a small hole is bored through both ends in the center of the scarf, the ends are separated, and a hardwood dowel about  $\frac{3}{8}$  in. in diameter is driven into one piece. Laminas are then ready for glue spreading and final assembly.

## MISCELLANEOUS SCARF TYPES

Laminas are sometimes joined with elaborate finger, round, thread, serrated, dovetail, and tooth scarfs, but seldom if ever are such forms used commercially in structural members of fir and pine, although they are sometimes used in oak. See typical end joints in laminating manual reference <sup>8</sup> for various simple and elaborate scarf types.

## SCARF-JOINT SPACING

In any member which is to be subjected to full or moderate bending stresses the laminas should be so assembled in the member as to dis-

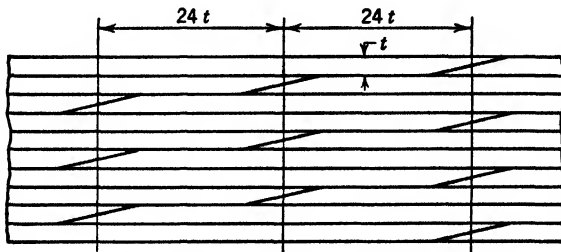


FIG. 3-10. Scarf-Joint Spacing.

perse thoroughly the end joints. No joint should be directly adjacent to another in adjacent pieces, nor, with scarfed joints sloping in the same direction, should joints be closer together in adjacent pieces than the length of the scarf nor closer together than  $24t$ . See Fig. 3-10 for preferred minimum spacing of scarf joints.

### EDGE JOINTS

For wide members a lamina may consist of two or more pieces of lumber placed side by side to form the full width if all longitudinal joints in adjacent laminas are staggered 2 in. or more laterally. Top- and bottom-face laminas of members should be in single pieces or of pieces edge-glued. Some authorities limit edge-joint stagger in adjacent laminas only to the thickness of one lamina.

Edge joints should be glued when the design requires full cross-section bending strength under loads which act parallel to the wide faces of laminas.

### NAIL PRESSURE

Glued members have been constructed and sometimes successfully so with nails to provide glue pressure. Often such nailing practice has been employed in job-site assembly. Tests have proved nail pressure to be inadequate, and, if it is used, inferior or doubtful quality merchandise may result. Nailing should only be used when clamping pressures are unobtainable and where substandard members are acceptable.

### GLUES

Space limitations prohibit description of glues and gluing techniques in this chapter.\* Glued construction predicates glue lines as strong and durable as the wood itself; that is, test breaks must be wood and not glue-line failures. Members intended for indoor protected service may use water-resistant glues, but those subject to extreme service conditions or to pressure treatment must use waterproof glues.

### STRUCTURAL TYPES

#### ARCHES

Glued members make the best type of timber arch since higher compression stresses may be used than in solid timbers and a higher bending stress than in laminated members.

Stresses in timber arches are computed by standard engineering formulas. Two-hinged arches are indeterminate in design, difficult to splice, and difficult to ship unspliced. Three-hinged arches are deter-

\* For a comprehensive discussion of adhesives see Chapter 2.

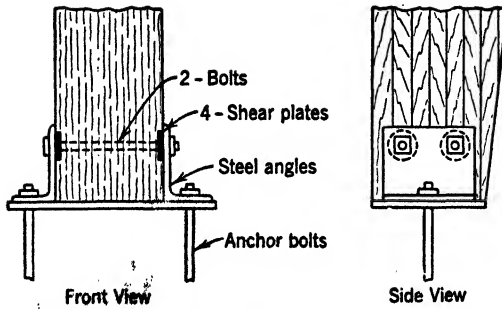


Fig. 3-11. Typical Anchorage to Foundations.

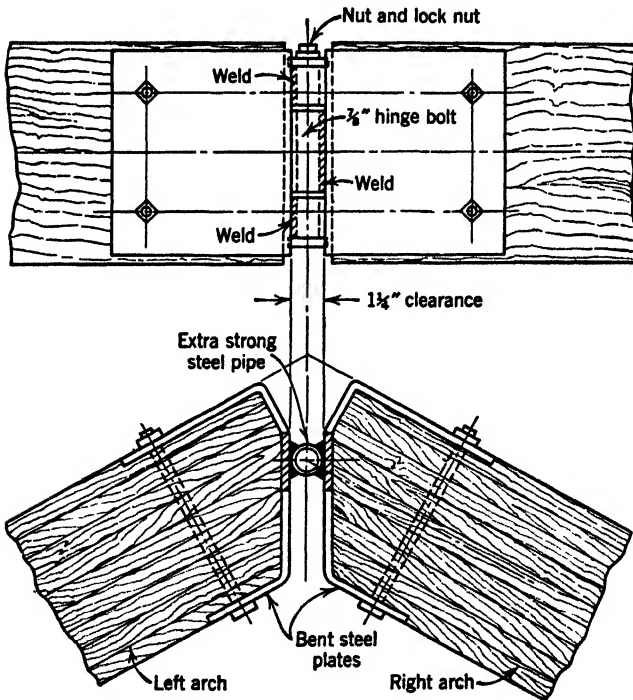


Fig. 3-12. Arch-Crown Hinge.

minate in design, have simple no-moment splices at their centers, and are already in two lengths for shipment. Three-hinged timber arches are most often used. (See arch design methods in "Glued-Laminated Wooden Arch."\*)

Zone grade selection may be used to good advantage in many arches. Since arches are often left exposed and are used in places where people congregate, good appearance is highly desirable. Arch shapes may be

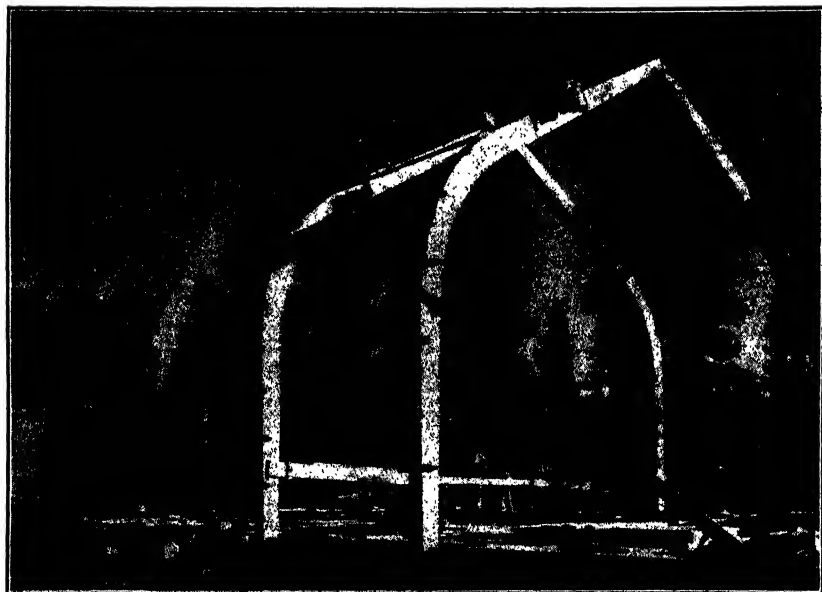


FIG. 3-13. Three-Hinged Glued Chapel Arches Being Erected. Span, 37 ft; rise, 27 ft.

circular, semicircular, variable radius, boomerang, or gothic. In Figs. 3-13, 3-14, and 3-15 are shown several arch types.

Base shoes of arches should provide adequate resistance to both horizontal thrust and vertical reaction (see Fig. 3-11). The crown splices of three-hinged arches have a hinge action which transmits thrust but not moment. Many such arches have been constructed with square abutting surfaces on arch ends and simple outer splice plates. In such an arrangement dead loads produce some settlement, lower corners separate slightly, and upper corners receive excessive pressure causing crushing and splitting which results in partial failure and poor appearance. Careful designers provide metal thrust plates or, still better, real hinges such as shown in Fig. 3-12.

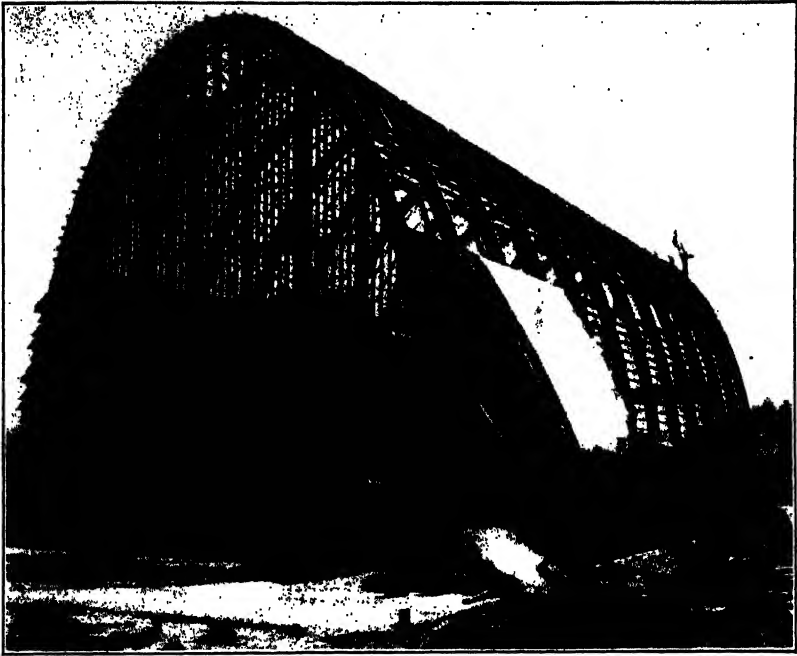


FIG. 3-14. Erection of Glued Arches for Radar Test Laboratory. Span, 80 ft; height, 78 ft; spacing, 16 ft 8 in.; each arch 10 ft 31 in.; 1 $\frac{3}{4}$ -in. laminas; three-hinged.

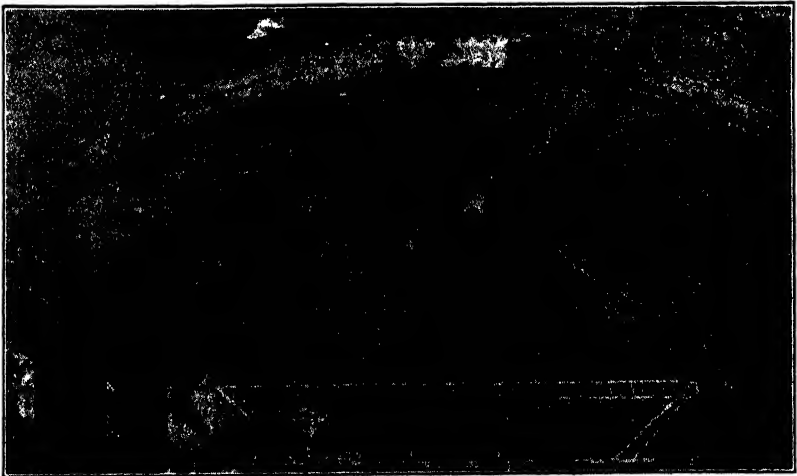


FIG. 3-15. Two-Hinged Glued-Laminated Arches Being Erected for Swimming Pool. Span, 77 ft.

## TRUSSES

Glued members make excellent truss chords, either curved or straight (Fig. 3-16). For curved chords they provide the neatest and safest type known. Ledgers may be built into chords for roof or ceiling joist support, and ends of chords at truss heels may be flared to give ample connection area. Glued timbers make fine straight lower chords which have a better appearance than solid timbers. For all truss chords large sizes (Fig. 3-17) may be safely made as glued members.

Curved glued chords take secondary bending stresses much better than laminated curved chords and thus permit construction of safer crescent, bowstring, and curved lower-chord trusses with fine appearance. Glued truss chords in compression may be made smaller than in laminated or in solid timbers because of the higher compressive stresses permitted.

## GIRDERS

Glued girders should be constructed with adequate camber in order that normal deflection will not cause sag below a straight line. Girders continuous over two or more spans should have a camber in each such span. It is recommended that minimum camber be equal in amount to the deflection computed under full dead and live load, a modulus of elasticity of 1,600,000 being used for fir and pine and 1,500,000 for white oak. Roof girders should use snow combined loading stresses and floor girders permanent loading stresses. Figure 3-14 shows a laminated girder over the door opening.

## COLUMNS

Glued members make fine columns since they do not check and split. Glued columns can be made smaller, strength for strength, than solid-timber columns. Zone selection is advantageous where columns are stressed in bending due to wind, and this condition is the critical design factor.

## FARM STRUCTURES

Glued members are widely employed as farm barn rafters (Fig. 3-18) as well as light supports for sides and roofs of brooder houses, hog-houses, poultry houses, cornercribs, implement sheds, stock sheds, garages, tenant houses, and other light farm structures.



FIG. 3-16. Bowstring Trusses. 202-ft span; glued-laminated top and bottom chords; trusses, 30-ft centers. Front trusses support heavy door loads in addition to roof loads.

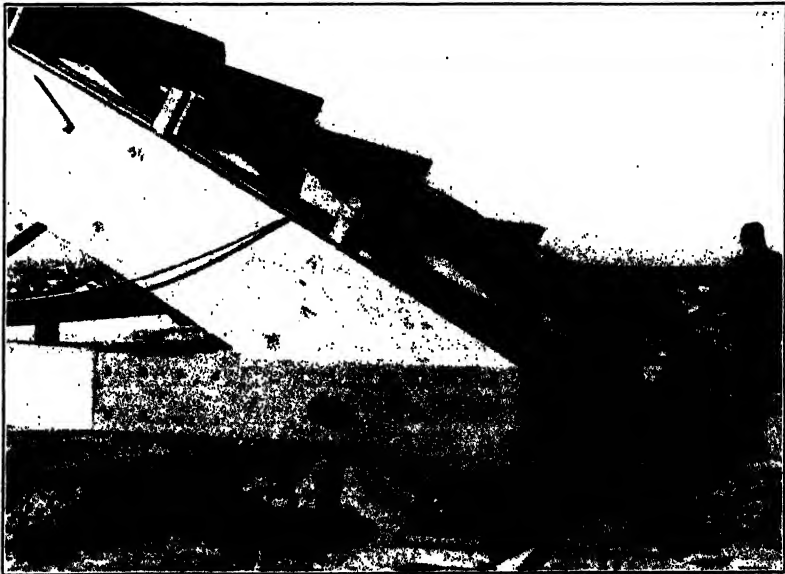


FIG. 3-17. Heel Connection of 222-ft-Span Bowstring Trusses. Glued-laminated top and bottom chords. At time of erection held record in United States for timber bowstring trusses.



Because barns stand outside congested areas and are buildings in which people do not congregate, glued-laminated barn rafters are commonly designed for lighter loads and higher working stresses than are

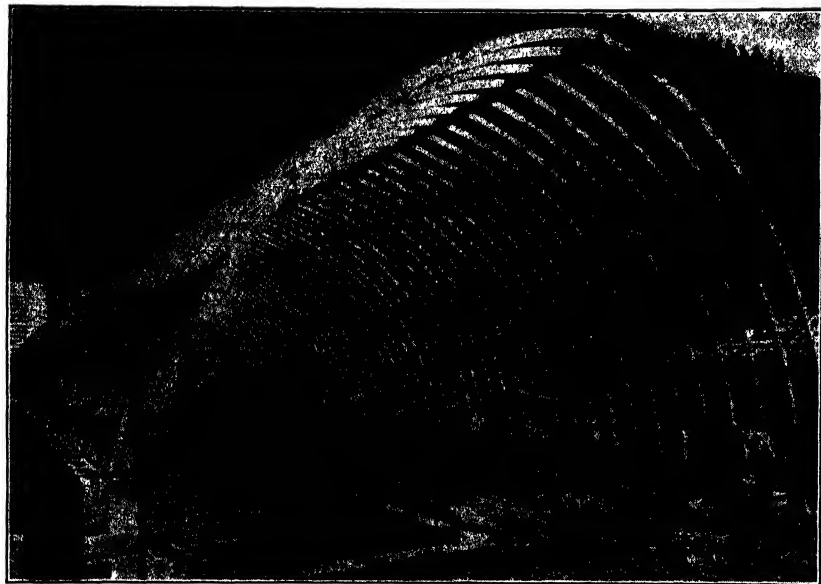


FIG. 3-18. Glued-Laminated Barn Rafters.

urban commercial structures. When barn rafters are used as arches in city commercial buildings, they must be closely spaced.

### BRIDGES AND TRESTLES

In bridges the top and bottom chords as well as floor beams of pony spans can well be glued timbers. In short-span bridges glued timbers can span from abutment to abutment and form low-cost girder bridges. Timber truss bridges are practical for spans up to 100 ft and timber girder bridges for spans up to 60 ft.

All permanent timber bridges should have handrails painted and the remainder of the material, either solid or glued, should be heartwood of durable species and should be pressure-treated. Hardware should be given a shop coat of red lead and oil or be galvanized.

Glued treated girders intended for use as railroad trestle stringers have been built and thoroughly tested. Sample installations have been

made to permit observation under actual conditions. It appears that for special long-span trestles glued treated members may well prove suitable.

#### DREDGE SPUDS

Dredges use steel or timber spuds as legs to anchor themselves to the bottom against wind and current. Timber spuds often must be of large size such as 30 in. square by 80 ft long (Fig. 3-19). Spuds are

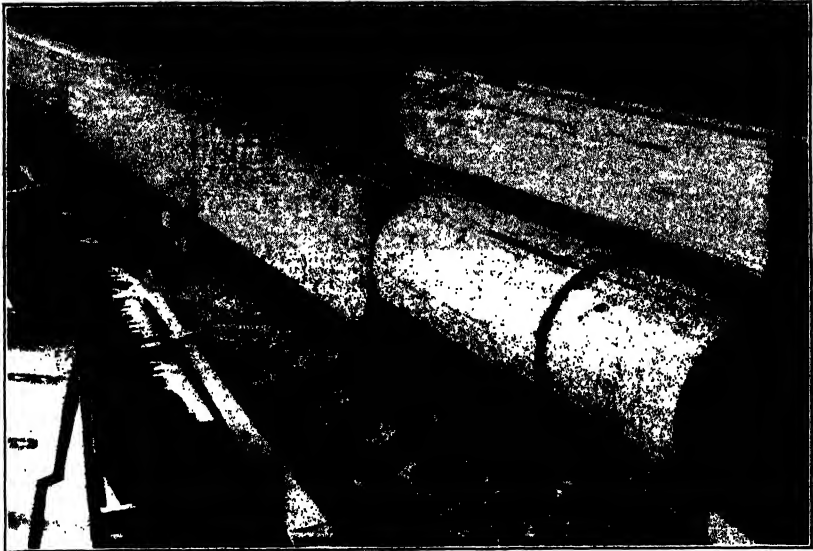


FIG. 3-19. Dredge Spud 30 in. by 30 in. by 85 ft Being Fabricated in Shop.

becoming difficult to secure in solid timbers, and glued members must be used. Waterproof glue is required, but sticks are seldom treated against decay since wear and breakage determine their length of life.

#### SHIP PARTS

During World War II, to promote the greatest possible utilization of gluing technique the United States Bureau of Ships sponsored contracts to develop glued construction to withstand the severe service conditions of repeated soakings and immersions in fresh or salt water of maritime use.

Contracts utilizing Douglas fir and white oak were performed by laminators on the West Coast and in the Middle West. These contracts

developed processes which were completely satisfactory to the Bureau of Ships. As a consequence, it is now possible to glue strong and durable frames, masts, keels, stems, sternposts, and other ship and barge members <sup>14</sup> (Fig. 3-20). Waterproof glues and careful laminating

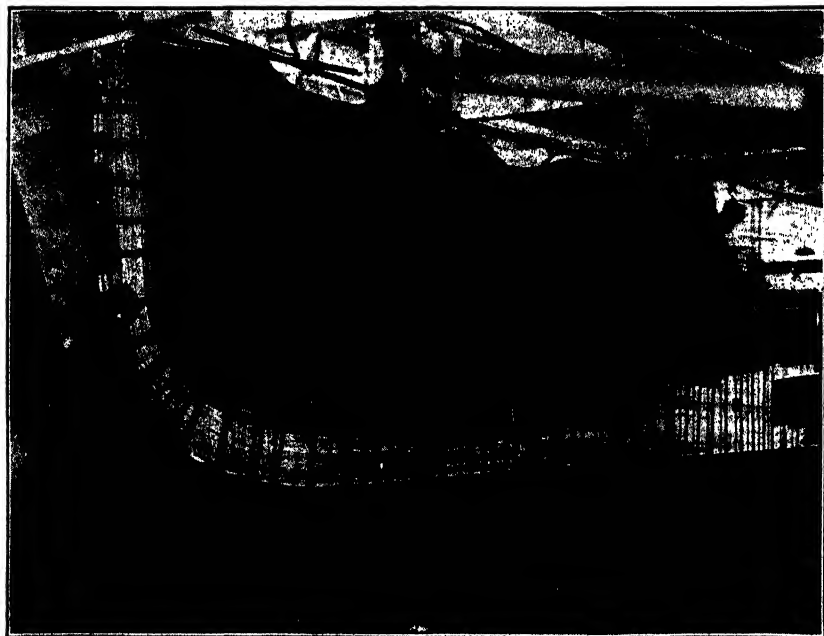


FIG. 3-20. One-Piece Stem, Keel, Shaft Log, and Horn Timber Assembly Glued-Laminated from Douglas Fir and Waterproof Glues.

and curing techniques are necessary to secure products which will withstand the extreme service conditions of maritime use. (See page 196, "Glues," and Chapter 2, "Adhesives.")

### GENERAL USES

#### CROSSARMS

Laminated crossarms for telephone and telegraph poles and line and terminal structures should reduce operation and maintenance costs and provide more continuous service. Several sets of laminated crossarms have been built and installed for service tests. These crossarms are placed in definite accessible locations, and service records are being kept to determine their value.

Laminated crossarms can be used in the standard 4-in.-by-5-in.-by-10-ft size for open circuits, but laminated material is more adaptable for large heavy-duty use on carrier lines or terminal structures where arms may be 30 to 40 ft long and support high-voltage lines.

Electrical tests indicate that glued crossarms reduce electric field disturbances many times in comparison with solid-wood members.

#### **DIVING BOARDS**

Glued diving boards when built of well-selected clear straight vertical-grain stock make a superior product.

#### **MISCELLANEOUS**

Glued members have been used for trailer reaches, truck beds, furniture stock, machinery parts, mine guides, gangplanks, pallets, ladder rails, boat paddles, tubes, plane parts, flagpoles, chopping blocks, and panels of many sorts.

### **FABRICATION TREATMENT**

#### **FABRICATION**

Glued members may be trimmed, bored, routed, dapped, and otherwise shaped by the same tools and the same machines and in the same manner as solid timbers. Hardware, ironwork, and all types of timber connectors function in laminated members as well as or better than in solid timbers.

#### **PREFABRICATION**

Glued members are nearly always completely prefabricated at a laminating plant. Corners are eased or chamfered, ends are trimmed, holes are bored, and routings cut.

### **TREATMENTS**

Joints in glued members bonded with phenol, resorcinol, or melamine glue and adequately cured for extreme service conditions are not affected by hot or cold water, oils, or most chemicals that do not damage wood. Tests made on glued members, though not extensive nor exhaustive, indicate that such glued members may be treated with any commercially used wood preservative or fire retardant, without ap-

preciable injury to the glue line. Tests to date are limited, and further study may cause slight revision in these conclusions.

Little information is available concerning the ability of glues to bond laminas already treated.<sup>15</sup> Oil-borne treatments may leave residues on surfaces that interfere with the bonding action of glues. The use of light oils and resurfacing help but do not cure the difficulty. Water-borne chemicals raise the grain, cause variable thicknesses, leave deposits which may not be compatible with the glue, and may leave the lumber with excessive or too variable moisture content. Most certainly operations of treating before gluing are critical operations and should be undertaken only after careful and exhaustive tests of the particular materials and combinations used.

### PROTECTION

Glued members built with water-resistant glues and intended for indoor use must be protected from exposure during manufacture, transit, and erection. They should be given end seals and protective side coatings during manufacture and should be protected from the weather during transportation and storage. Weather discoloration degrades appearance although no structural damage may occur. Glued members built with waterproof glues and intended for indoor always-dry service need protection during transportation and storage only against weather discoloration.

Glued members built with waterproof glues and intended for outdoor service should be heartwood of a durable species or should be given a preservative treatment. They need no extra protection.

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## CHAPTER 4

# Plywood

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### DEFINITION

Plywood is a built-up board or panel, consisting of an odd number of veneer sheets placed crosswise and bonded together with a suitable adhesive. Since most construction plywood is of Douglas fir, the data in this section are devoted chiefly to plywood of that species.

### MANUFACTURE

Douglas fir trees from forests on the western slopes of the Cascades and the coastal plains of the Pacific furnish the "peeler" logs used in making Douglas fir plywood.

Forty-odd plants in Western Washington and Oregon, with a rated annual capacity of more than 2 billion square feet, transform these logs into plywood. The basic manufacturing steps are peeling the veneer, clipping and sorting, drying, gluing and panel assembly, pressing, trimming and cutting panels to accurate size, sanding, and final grading.

### TWO BASIC TYPES

Douglas fir plywood is produced in two basic types: (1) Exterior or waterproof (intended for permanent outside exposure), in which the veneers are bonded with a hot-pressed phenolic resin adhesive that is insoluble under practically any exposure, including boiling, and, (2) Interior or moisture-resistant, usually made with a protein or extended resin adhesive in either a hot or a cold press. It is intended for permanent inside uses where the moisture content of the wood does not exceed 20 per cent. Several appearance grades, designed to fit varying construction and industrial needs, are available in each of the two types.

## GENERAL USES

Prior to Pearl Harbor, plywood was finding a wide and increasing application in building construction for such purposes as subfloors, sheathing of walls and roofs, interior paneling and all kinds of concrete form work. Industrial applications also accounted for a large volume.

After 1938, when rigid performance standards and grade marking were adopted by the Douglas fir plywood industry, the Exterior type was produced in ever-increasing amounts for building exteriors, outdoor signs, various marine uses, and other severe services. Interior-type plywood uses also increased so that by 1942 nearly 2 billion square feet were consumed annually.

During the war, most plywood was consigned to critical war uses, ships and small boats, pontoons, aircraft, overseas hutments, barracks and housing at home and abroad, special boxes and crates, and hundreds of special applications as American ingenuity applied itself to war.

Concurrently a tremendous research program was being conducted at the U. S. Forest Products Laboratory on the mechanical and physical properties of plywood, structural design, durability of adhesives and other factors of interest to engineers. Such data when disseminated will undoubtedly lead to a broader acceptance of plywood in construction.

## SIZES

Douglas fir plywood is generally available in panels 4 ft wide by 8 ft long, but 9- and 10-ft lengths may also be procured in normal times. In addition several plywood manufacturers produce Exterior panels up to 50 ft long (or wide) by scarf-jointing 4-ft-by-8-ft panels. These larger panels are structurally equivalent to single sheets, as the strength and durability of the scarf joint equals that of the Exterior glue line itself.

Thicknesses vary with the grades but range generally from  $\frac{3}{16}$  to  $1\frac{3}{16}$  in. Most commonly used are  $\frac{1}{4}$ ,  $\frac{3}{8}$ ,  $\frac{1}{2}$ ,  $\frac{5}{8}$ , and  $\frac{3}{4}$  in.

Grades and types with performance tests and dimensions are in accord with industry standards as set forth in U. S. Commercial Standard CS45-47.\* Each panel carries an identifying grade mark to denote conformity with the standard and to enable the consumer to identify the type and grade.

\* Available from Government Printing Office, Washington, D. C., at 10¢ per copy.



**ADHESIVES \***

Modern plywood adhesives bond the veneers together so that the wood will fail under stress before the glue joint. This holds true also of the best assembly glues used for wood arches, built-up girders, and prefabricated panels in which plywood is glued to both sides of a lumber framework.

The Douglas fir plywood industry, through its Association, has established a rigid control system to maintain manufacturing quality, and especially glue bonding, at a high quality level.

Approximately a quarter of a million plywood specimens are tested annually in the Association's laboratory. Exterior-type pieces are boiled 4 hr, dried 20 hr at 145°F, boiled again, and then broken wet in a tension-shear machine, where a high percentage of wood failure over the fractured area is required.

The necessity for this high wood failure in test specimens as an indication of future durability of Douglas fir plywood has been well established over nearly a decade through laboratory tests running literally into the hundreds of thousands, with correlated field exposures on nearly 10,000 small panels.

Interior- (moisture-resistant) type Douglas fir plywood also must pass performance standards which consist of ten cycles of soaking and drying of 6-in.-square pieces without significant delamination. This test, once used only for the concrete form grade, is now the criterion of durability for all Interior grades of Douglas fir plywood.

**PHYSICAL PROPERTIES**

The construction of a plywood panel by cross-laminating veneers and gluing them together capitalizes on the more desirable physical properties of wood. Wood is many times stronger along the grain than across the grain. Moreover, wood has virtually no expansion or contraction along the grain, even with large changes in moisture content; further, wood has no cleavage plane across the grain and, consequently, cannot split in that direction.

In plywood, since adjacent plies are placed crosswise to each other, longitudinal grain is provided both lengthwise and crosswise of the panel. Consequently, plywood functions effectively as a structural diaphragm or as a bracing, and also where plate action, with all edges supported, is involved. The cross lamination in plywood tends to equalize

\* See Chapter 2, "Adhesives," for detailed discussion of adhesives, including those used in the plywood industry.

the properties in each direction and to minimize, if not entirely eliminate, certain weaknesses.

Shrinkage, for example, is reduced in plywood so as to be negligible in many services.

Splitting is impossible in any direction; consequently nailing properties are good.

Bending strength and stiffness, although reduced somewhat lengthwise of the panel, are greatly increased crosswise, the amount varying with the number and thickness of plies. The greater the number of plies, of course, the nearer the equalization of strength in the two directions.

#### MISCELLANEOUS PROPERTIES

Plywood has the same coefficient of thermal conductivity as the species of wood from which it is made. For Douglas fir, the value commonly used is 0.78 Btu per hour per square foot per degree Fahrenheit temperature difference. Plywood although not generally considered as an insulation material provides an air-tight finish that minimizes heat loss.

This very air-tightness of plywood, however, also prevents the ready escape of moisture vapor. Accordingly, even though vapor will penetrate rather slowly through plywood, it is desirable where high humidities obtain within a plywood-lined structure to provide ventilation for all concealed air spaces.

Attics or lofts, under plywood or any tight roof sheathing, are typical examples of spaces requiring such ventilation particularly under vapor-tight roofings. On the other hand, plywood-interior wall or ceiling finish with a coat of asphalt paint or glossy-surfaced building paper provides a highly effective vapor barrier to prevent condensation within walls.

Plywood will attain an equilibrium moisture content of 20 per cent, the maximum for safe use of "interior"-type material, at a relative humidity of 86 per cent at 70°F. Prolonged exposure at higher humidities brings wood into the zone where mold and fungus growth may start. Humidities of 80 per cent at 70°F will not create a moisture content of more than 17 per cent which is safe. Under ordinary service conditions, the moisture content of wood or plywood will not go under 5 per cent or above 15 per cent.

Acoustically, plywood has a sound absorption coefficient of about 0.16, compared to 0.04 for hard wall finishes, based on tests at the Riverbank Laboratories. The sound reduction factor, with  $\frac{1}{4}$ -in. ply-

TABLE 4-1. APPROXIMATE METHODS OF CALCULATING THE STRENGTH OF PLYWOOD—DESIGN METHOD AND ALLOWABLE STRESSES \*†

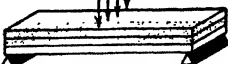
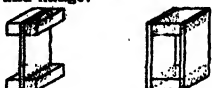




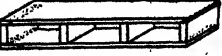
Property	Direction of Stress with Respect to Direction of Face Grain	Area to Be Considered	Unit Stress to Be Used
Tension	Parallel or perpendicular	Parallel plies ‡ only	Unit stress for extreme fiber in bending
	±45°	Full cross-sectional area	One-sixth unit stress for extreme fiber in bending
Compression	Parallel or perpendicular	Parallel plies ‡ only	Unit stress in compression parallel to grain
	±45°	Full cross-sectional area	One-third unit stress in compression parallel to grain
Bearing at right angles to plane of plywood		Loaded area	Unit stress in compression perpendicular to grain
Load in bending	Parallel or perpendicular	Bending moment $M = KSI/c$ where $S$ = unit stress for extreme fiber in bending; $I$ = moment of inertia computed on basis of parallel plies only; $c$ = distance from neutral axis to outer fiber of outermost ply having its grain in the direction of the span; $K = 1.60$ for three-ply plywood having the grain of the outer plies perpendicular to the span; $K = 0.85$ for all other plywood	Unit stress for extreme fiber in bending
Deflection in bending	Parallel or perpendicular	Deflection may be calculated by the usual formulas, taking as the moment of inertia that of the parallel plies plus 1/20 that of the perpendicular plies. (When face plies are parallel, the calculation may be simplified, with but little error, by taking the moment of inertia as that of the parallel plies only.)	Unit value for modulus of elasticity
Deformation in tension or compression	Parallel or perpendicular	Parallel plies ‡ only	Unit value for modulus of elasticity
Shear through thickness	Parallel or perpendicular	Full cross-sectional area	Double unit stress in horizontal shear
	±45°	Full cross-sectional area	Four times unit stress in horizontal shear

\* Reprinted from *USDA Forest Products Lab. Mimeo. R1630, Approximate Methods of Calculating the Strength of Plywood*, by L. J. Markwardt, assistant director, and A. D. Freas, engineer. Revised October 1946.

† The suggested simplified methods of calculation apply reasonably well with usual plywood types under ordinary conditions of service. It is recognized, however, that they are not entirely valid for all types of plywood and plywood constructions, or for all spans and span-depth ratios. Also the methods given are not applicable to structures so proportioned that the plywood is in the buckling range, in which event the results will be too high.

‡ By "parallel plies" is meant those plies whose grain direction is parallel to the direction of principal stress.

**TABLE 4-1. APPROXIMATE METHODS OF CALCULATING THE STRENGTH OF  
PLYWOOD—DESIGN METHOD AND ALLOWABLE STRESSES (Continued)**

Property	Direction of Stress with Respect to Direction of Face Grain	Area to Be Considered	Unit Stress to Be Used
Shear in plane of plies	Parallel or perpendicular	Full shear area. 1. Plywood beams. Horizontal shear: 	1. Three-fourths unit stress in horizontal shear
		Area of contact between plywood and flange or framing member. 2. I or box beams with plywood webs. Shear between plies of web or between web and flange: 	2. Three-eighths unit stress in horizontal shear
		3. Panels having plywood covers stressed in compression or tension, or both. Shear between plies or between cover and framing members when depth of member exceeds twice its width and end headers are used or when depth is not more than twice the width and no headers are used. A. Interior framing members:  B. Framing members at edge of panel: 	3. A. Three-fourths unit stress in horizontal shear B. Three-eighths unit stress in horizontal shear
	±45°	Area of contact between plywood and flange or framing member. 1. I or box beams with plywood webs. Shear between plies of web or between web and flange: 	1. One-half unit stress in horizontal shear
		2. Panels having plywood covers stressed in compression, or tension, or both. Shear between plies or between cover and framing members when depth of member exceeds twice its width and end headers are used or when depth is not more than twice the width and no headers are used. A. Interior framing members:  B. Framing members at edge of panel: 	2. A. Unit stress in horizontal shear B. One-half unit stress in horizontal shear

wood on each side of a 2-in.-by-4-in. frame wall, is 31.1 decibels, comparing favorably with other conventional materials.

### DESIGN

Working stresses for plywood are based on the strength properties and "basic stresses" for wood, as determined by the U. S. Forest Products Laboratory.

Suggested methods of applying basic wood stresses to plywood design have been outlined by the U. S. Forest Products Laboratory in their bulletin, "Approximate Methods of Calculating the Strength of Plywood" (shown in Tables 4-1, 4-2, and 4-3, pages 212-216).

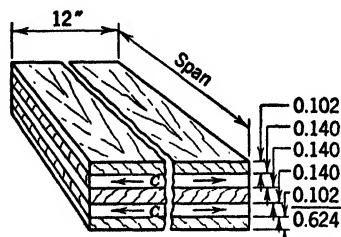


FIG. 4-1. Typical Computation for Moment of Inertia,  $I$ .

$$I \text{ (for 12" width)} = \frac{1}{2} \left[ \left( \frac{5}{8} \right)^3 - (3 \times 0.14)^3 + 0.14^3 \right]$$

or

$$I = 0.173 \text{ in.}^4$$

If the grain of the face plies runs at right angles to the span then only the crossbands  $c$  would be considered in computing the

$$I = \frac{1}{2} \left[ (3 \times 0.14)^3 - 0.14^3 \right] = 26 \times 0.14^3 = 0.071 \text{ in.}^4$$

### STRENGTH PROPERTIES: TENSION, COMPRESSION, AND FLEXURE

When plywood is subjected to a tensile or compressive force lengthwise, only those plies having their grain running lengthwise are considered as carrying the load. The cross plies, of course, are stressed across the grain and so are incapable of contributing any significant amount to the strength of plywood in tension or compression.

Similarly, in bending or flexure, only the plies running parallel to the span are considered in most cases in computing the moment of inertia  $I$  of the cross section. When plywood is used so that the grain of the exterior plies (face grain) runs parallel to the span, the error (on the safe side) in neglecting the perpendicular-to-the-span plies is quite small, being less than 1 per cent in a  $\frac{1}{4}$ -in. panel, about 4 per cent in a 1-in. panel, and almost never exceeding 5 per cent.

When plywood is used in flexure with its face grain perpendicular to the span (that is, parallel to the support), the face plies will contribute considerably to the stiffness, and may contribute to the strength of a three-ply panel, provided they consist of single sheets of veneer or of several narrow strips edge-glued to form the wide face. For example, in a  $\frac{3}{8}$ -in. panel with three  $\frac{1}{8}$ -in. plies, the  $I \perp$  \* for a 12-in. width, considering only the center ply, is .0020 in.<sup>4</sup>.

TABLE 4-2. APPROXIMATE METHODS OF CALCULATING THE STRENGTH OF PLYWOOD—BASIC STRESSES FOR DOUGLAS FIR (COAST REGION) FREE FROM DEFECTS \*

Property	Psi
Extreme fiber in bending	2,000
Compression perpendicular to grain	325
Compression parallel to grain	1,466
Maximum horizontal shear	120
Modulus of elasticity	1,600,000

Appropriate unit stress for Table 4-1 may be obtained from Table 4-2 by multiplying the basic values by the appropriate reduction factor, as follows:

1. For Douglas fir plywood to be used in dry locations (moisture content 16 per cent or less), the basic stresses for extreme fiber in bending, compression perpendicular to grain, and compression parallel to grain may be increased by 25 per cent. (No increase for maximum horizontal shear or modulus of elasticity.)
2. The basic stresses are for clear wood without defects. An appropriate reduction factor is to be used according to the estimated grade of material with respect to defects allowed. When defects present are estimated to reduce the strength one fourth, multiply the basic stresses by three fourths, etc.

*Example:* What unit stress should be used for tension parallel to face grain for plywood of a three-fourths grade to be used in dry locations?

*Procedure:*  $2000 \times 1.25 \times 0.75 = 1875$  psi.

\* Reprinted from *USDA Forest Products Lab. Mimeo. R1630, Approximate Methods of Calculating the Strength of Plywood*, by L. J. Markwardt, assistant director and A. D. Freas, engineer. Revised October 1946.

Source: *USDA Misc. Pub. 185, Guide to the Grading of Structural Timbers*. Basic stresses for some other species are given in Table 8 of *USDA Misc. Pub. 185*.

If, however, we consider the face plies also, and the fact that the modulus of elasticity  $E$  for wood in flexure across the grain equals about  $\frac{1}{20}$  that along the grain, the effective  $I \perp = 0.0020 + (\frac{1}{20}I \parallel = 0.0025) = 0.0045$  in.<sup>4</sup>. In five-ply panels, the increase in  $I \perp$  from adding  $\frac{1}{20}I \parallel$  is much less significant, as may be seen from values in Table 4-5, page 222.

\* For convenience in referring to the moments of inertia of plywood lengthwise and crosswise,  $I \parallel$  will be used to designate the  $I$  when the face grain is parallel to the span, and  $I \perp$  will designate  $I$  where the face grain is perpendicular to the span.

Since there is no assurance of getting faces made of a single piece of veneer, except in special cases, and since edge gluing of strips to form

TABLE 4-3. APPROXIMATE METHODS OF CALCULATING THE STRENGTH OF PLYWOOD—EXAMPLES OF UNIT STRESSES FOR DOUGLAS FIR PLYWOOD OF THREE-FOURTHS GRADE TO BE USED IN DRY LOCATIONS, FOR USE WITH TABLE 4-1 \*

Property	Direction of Stress with Respect to Face Grain	Psi
Tension	Parallel or perpendicular	1,875
Tension	$\pm 45^\circ$	310
Compression	Parallel or perpendicular	1,375
Compression	$\pm 45^\circ$	466
Shear	Parallel or perpendicular	180
Shear	$\pm 45^\circ$	360
Shear in plane of plies	Parallel or perpendicular	34 †
Bending	Parallel or perpendicular	1,875
Modulus of elasticity	Parallel or perpendicular	1,600,000
Compression perpendicular to grain (bearing)		400

\* Reprinted from *USDA Forest Products Lab. Mimeo R1630, Approximate Methods of Calculating the Strength of Plywood*, by L. J. Markwardt, assistant director, and A. D. Freas, engineer. Revised October 1946.

† Applies to shear stresses, such as in I and box beams, where the stress is concentrated at the inner edge of the flange. For other conditions as outlined in Table 4-1, different values would be found as calculated by the appropriate factor.

wide veneer is not done in all mills, it is considered sound and entirely satisfactory practice generally to disregard the effect of all plies run-

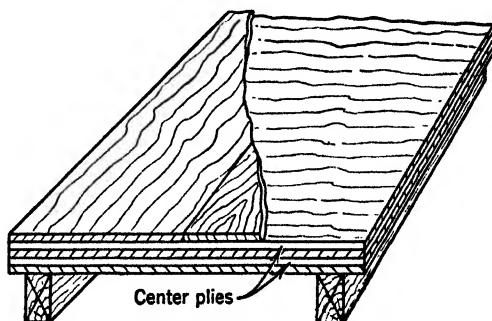


FIG. 4-2. Only Center Plies Run Parallel to Span. Face Plies, therefore, are generally ignored in computing *I*.

ning perpendicular to the span (Figs. 4-2 and 4-3), except in considering the stiffness of panels with face grain perpendicular to span, since

stiffness is little affected by lack of edge gluing veneers. (See also page 212, Forest Products Laboratory reprint, Table 4-1, "Deflection in Bending.")

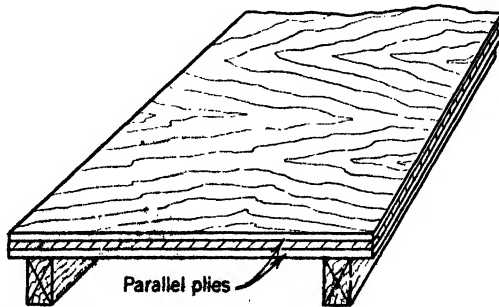


FIG. 4-3. Both Face Plies Run Parallel to Span, and Center Ply Is Generally Ignored in Computing  $I$ .

## SHEAR

Shearing stresses in plywood are of two distinctly different types, either one of which may be the critical factor in design. One kind of shear is that perpendicular to the plane of the panel, as horizontal (or vertical) shear in a built-up beam with a plywood web. This shear is computed over the full cross-sectional area of the panel, using an allowable stress of twice the basic horizontal shear stress for clear Douglas fir, that is, twice 120 psi, with suitable reduction for the plywood grades.

A common example of this type of shear is in plywood used as wall sheathing or as a diaphragm in designing against earthquakes. Panels must be adequately nailed to the framing (see page 236 on lateral bearing of nails), of course, or glued, if anything like the full shear strength of the plywood is to be developed.

The second type of shear is that in the plane of the glue joint, or with plywood, in the "glue line" between veneers. When the grain of contiguous pieces of laminated wood is parallel, the full unit stress for horizontal shear, in clear wood of the same species, may be used.

When plywood, however, with its cross-laminated veneers is subjected to shear in the plane of the plies, the wood fibers in the ply at right angles to the principal shearing force tend to "roll," and a so-called "rolling shear" is induced. Resistance of plywood against this is only about one-third that offered by wood parallel to the grain but because of beam checking and other lumber factors the Forest Products



Laboratory suggests a unit shear "in plane of plies" of three-fourths the basic horizontal shear of 120, or 90 psi.

A series of more than 300 "rolling shear" tests in the Douglas Fir Plywood Laboratory, on plywood of various thicknesses, gave an average stress of 365 psi with range of 565 down to 180. The wide range in values appeared to be associated with the small size of the test specimens, in which the shear area was only a few square inches. When structural members of various shapes have been loaded so as to fail in rolling shear, the computed stresses have never been so low as the mini-

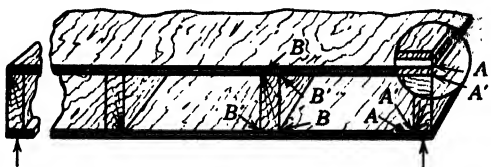


FIG. 4-4. Built-up Panel with Stressed Covers (Plywood Glued to Frame). If the plywood has its face plies parallel to the joists, the critical shear ordinarily will be at *A* or *B*, in the plane of the plies, rather than at *A'* or *B'* where the fibers in the face of the plywood and in the joist are parallel. At *A*, above the "outside joist," only one-quarter the unit shear stress is to be used, whereas, at *B*, where "symmetrical" stress concentration is assumed, one-half the unit shear stress would be used (see Table 4-1). If the plywood runs perpendicular to the joists, these same unit shear stresses would then apply at *A'* and *B'* where the panels are glued to the joists and where "rolling shear" would occur.

imum values obtained from the small tests. In other words, when shear occurred over a large area localized "weak spots" were averaged out. These investigations have contributed to the establishment of the rolling shear stresses now recommended for Douglas fir plywood.

#### BOLT BEARING IN PLYWOOD

This is a measure of the compression strength of the various plywood veneers. It can be determined by using the projected bolt-bearing area of the plywood veneers and the unit stress values of 1375 for  $C_{\parallel}$  and 405 for  $C_{\perp}$  from Table 4-4. Here of course the perpendicular plies will contribute significantly to the bearing value, in contrast with their performance in flexure. Bearing at intermediate angles to the grain may be interpolated on a straight-line basis, according to Forest Products Laboratory tests.

In seven-ply  $\frac{3}{4}$ -in. plywood, for example, assuming a  $\frac{1}{4}$ -in. bolt loaded parallel to face grain, the area equals  $\frac{1}{4}$  times  $\frac{3}{8}$  for  $C_{\parallel}$  and the

**TABLE 4-4. RECOMMENDED WORKING STRESSES FOR PLYWOOD (DOUGLAS FIR)**

For Grades and Thicknesses Listed in US CS45-47

In bending, tension, and compression (except bearing and 45° stresses) consider only those plies with their grain direction parallel to the principal stress.

## Dry Location

Type of Stress	Exterior So2S	Exterior So1S, Exterior or Interior Concrete Form	Exterior or Interior Sheathing	Interior So2S and So1S (per cent) Apply the following percentages to the stresses for the corre- sponding exterior grade
<i>Extreme fiber in bending</i>				
Face grain    to span	2,188	2,000	1,875	100
Face grain ⊥ to span	1,875	1,875	1,875	80
<i>Tension</i>				
to face grain (3-ply only *)	2,188	2,000	1,875	100 †
⊥ to face grain	1,875	1,875	1,875	80
±45° to face grain	337	320	310	85
<i>Compression</i>				
to face grain (3-ply only *)	1,605	1,460	1,375	100 †
⊥ to face grain	1,375	1,375	1,375	70
±45° to face grain	496	472	460	80
<i>Bearing (on face)</i>	405	405	405	100
<i>Shear, rolling</i>				
In plane of plies and    or ⊥ to face grain	79	72	68	75
In plane of plies and ±45° to face grain	105	96	90	75
<i>Shear</i>				
In plane ⊥ to plies and    or ⊥ to face grain	210	192	180	85
In plane ⊥ to plies and ±45° to face grain	420	384	360	85
<i>Modulus of elasticity in bending</i>				
Face grain    to span	1,600,000	1,600,000	1,600,000	100
Face grain ⊥ to span	1,600,000	1,600,000	1,600,000	70

\* For tension or compression, || to grain, in 5-ply or thicker, use values for 3-ply, but in next lower grade.

† For 5 or more plies use 90%.

## Damp or Wet Location

Where moisture content will exceed 16 per cent, decrease by 20 per cent values shown for Dry Location for following properties:

Extreme Fiber in Bending, Tension and Compression both parallel and perpendicular to grain and at 45 degrees, and Bearing. (No change in values for shear or modulus of elasticity.)

Only Exterior type plywood should be used where moisture content will exceed 20 per cent.

same for  $C \perp$ . Therefore, total permissible load on  $\frac{1}{4}$ -in. bolt equals  $\frac{3}{32}$  times (1375 plus 405) or 167 lb.

This value should be compared with Forest Products Laboratory tests (see report "Bolt-Bearing Strength of Wood and Modified Wood," no. 1523) showing proportional limit bearing values of 600 to 900 lb for  $\frac{1}{4}$ -in. bolts in  $\frac{3}{4}$ -in. Douglas fir plywood. These values should be reduced to include a safety factor (usually 1.6 with proportional limit) to obtain permissible loads.

It was significant, as the Forest Products Laboratory points out, that for smoothly cut bolt holes bearing values were considerably higher than for poorly drilled holes.

In some cases the proportional limit was only one third in rough bolt holes as compared to smooth. It was found that a twist drill, at a speed of 2200 rpm, gave better results than at slow speed of 400 rpm or than a machine bit at any speed. Also a piece of plywood used underneath as a "chip breaker" when drilling improved the hole.

This indicates the possibility of higher bolt-bearing values if proper care is taken in preparing bolt holes.

#### WORKING STRESSES

In plywood grades the number and type of characteristics are limited chiefly by appearance requirements, by manufacturing economy, and by their natural occurrence in the veneer.

The working stresses in Table 4-4 are those recommended by the Douglas Fir Plywood Association and are derived from basic stresses determined by the Forest Products Laboratory.

#### TABULAR DATA

Table 4-5, page 222, lists the  $I_{\parallel}$  and  $I_{\perp}$ , together with section moduli and areas of veneers per foot of width for plywood used both parallel and perpendicular. In computing these tables, veneer thicknesses selected for the various panel thicknesses are for the most part those commonly employed by the manufacturer. When there is a variation in manufacturing practice in certain thicknesses, a conservative construction has been selected.

#### STIFFNESS

The values for  $I$  give immediately the comparative stiffness of different plywood thicknesses and may be substituted in the standard deflection formulas, except for three-ply perpendicular, as pointed out

in a previous paragraph (see also Forest Products Laboratory Reprint, Table 1, "Deflection in Bending," page 212).

#### STRENGTH

Similarly, values for  $I/c$ , or section moduli, give relative strengths in bending and are used with standard formulas, except that the Forest Products Laboratory recommends using the constant  $K$ , with bending-moment formula,  $M = KSI/c$  (see Table 4-1, "Load in Bending").

It is to be noted that  $c$  is the distance from neutral axis to outer fiber of *outermost ply running parallel* to span. This is important in panels used perpendicular to span.

It will be noted that  $I_{||}$  plus  $I_{\perp}$  equals the  $I$  of a cross section of solid wood of equal quality, and also that, as plywood increases in thickness, its strengths lengthwise and crosswise tend to equalize.

Area of veneer cross sections will be useful where tension or compression is involved.

Shear in either a horizontal or vertical plane, perpendicular to the face of a panel used flatwise or on edge, is computed across the full cross-sectional area of the panel.

#### DEFLECTION CHARTS

Figures 4-5 to 4-13, inclusive, represent graphically the deflection of Douglas fir plywood under a uniformly distributed load, when considered as a simple beam. Values are computed from the standard deflection formula,  $d = 5Wl^3/384EI$ . The charts are for plywood with the grain of the face plies parallel with the span.

When the plywood panels run with the face grain parallel with the supports, however, the stiffness is decreased so that deflection under a given load is greater. Accordingly, on each chart is shown a reduction factor to be applied to the chart load for any given deflection. This factor is simply the ratio of  $I_{\perp}$  plus  $\frac{1}{2} I_{||}$  to  $I_{||}$ , when values from Table 4-5 are used.

Plywood in construction is usually applied over multiple supports where it functions as a continuous beam, as for subflooring or roof decking. The maximum deflection in a continuous beam of equal spans and under uniform load occurs in the outer span and is approximately one-half the deflection of a simple beam of the same span and load.

Consequently, when plywood is used over three or more supports, *the chart loads that cause a given deflection may be doubled.*

TABLE 4-5. MOMENTS OF INERTIA, SECTION MODULI AND VENEER AREAS FOR SELECTED PLYWOOD CONSTRUCTIONS

12-in. Widths

Plywood Thickness (Net)	No. of Plies	Veneer Thick (Normal) in Inches			Parallel † Plies Only			Perpendicular ‡ Plies Only			Weight, lb per 1000 sq ft (Approx.) (as shipped from Mill)
		Centers			Section Modulus $S$ (in. <sup>3</sup> )	Moment of Inertia $I$ (in. <sup>4</sup> )	Area (sq in.)	Section Modulus $S$ (in. <sup>3</sup> )	Moment of Inertia $I$ (in. <sup>4</sup> )		
		Faces §	Crossband								
$\frac{1}{8}$ "—R *	3	$\frac{1}{24}$		$\frac{1}{24}$	1.00	0.0019	0.030	0.50	0.0001	0.0034	490
$\frac{1}{8}$ "—S †	3	$\frac{1}{16}$		$\frac{1}{16}$	0.75	0.0017	0.027	0.75	0.0002	0.0077	490
$\frac{3}{16}$ "—R	3	$\frac{1}{16}$		$\frac{1}{16}$	1.50	0.0064	0.068	0.75	0.0002	0.0077	640
$\frac{3}{16}$ "—S	3	$\frac{1}{12}$		$\frac{1}{12}$	1.25	0.0060	0.064	1.00	0.0006	0.0139	640
$\frac{1}{4}$ "—R	3	$\frac{1}{12}$		$\frac{1}{12}$	2.00	0.0150	0.120	1.00	0.0006	0.0139	790
$\frac{1}{4}$ "—S	3	$\frac{1}{6}$		$\frac{1}{6}$	1.67	0.0143	0.114	1.33	0.0014	0.0247	790
$\frac{5}{16}$ "—R	3	$\frac{1}{10}+$		$\frac{1}{10}+$	2.50	0.0294	0.188	1.25	0.0011	0.0215	950
$\frac{5}{16}$ "—S	3	$\frac{1}{6}$		$\frac{1}{6}$	2.25	0.0286	0.183	1.50	0.0020	0.0312	950
$\frac{3}{8}$ "—R	3	$\frac{1}{6}$		$\frac{1}{6}$	3.00	0.0509	0.271	1.50	0.0020	0.0312	1125
$\frac{3}{8}$ "—S	3	$\frac{1}{8}$		$\frac{3}{16}$	2.25	0.0461	0.246	2.25	0.0066	0.0704	1125
$\frac{3}{8}$ "—S	5	$\frac{1}{10}$		$\frac{1}{12}$	2.50	0.0377	0.201	2.00	0.0150	0.120	1125
$\frac{7}{16}$ "—R	3	$\frac{1}{6}$		$\frac{1}{16}$	3.00	0.0772	0.353	2.25	0.0066	0.0704	1300
$\frac{7}{16}$ "—R	5	$\frac{1}{10}$		$\frac{1}{12}$	3.25	0.0688	0.314	2.00	0.0150	0.120	1300
$\frac{7}{16}$ "—S	5	$\frac{1}{10}$		$\frac{1}{10}$	2.85	0.0575	0.263	2.40	0.0260	0.1735	1300
$\frac{1}{2}$ "—R	5	$\frac{1}{10}$		$\frac{1}{10}$	3.60	0.0990	0.396	2.40	0.0260	0.1735	1525

# Deflection Charts

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$\frac{1}{2}$ "-S	5	$\frac{1}{8}$	$\frac{1}{8}$	2 @ $\frac{1}{10}$	3.60	0.0926	0.370	2.40	0.0324	0.1995	1525
$\frac{3}{16}$ "-R	5	$\frac{1}{8}$	$\frac{1}{8}$	2 @ $\frac{1}{10}$	4.35	0.1457	0.517	2.40	0.0324	0.1995	1675
$\frac{3}{16}$ "-S	5	$\frac{1}{8}$	$\frac{1}{8}$	2 @ $\frac{1}{8}$	3.75	0.1273	0.452	3.00	0.0507	0.271	1675
$\frac{5}{8}$ "-R	5	$\frac{1}{8}$	$\frac{1}{8}$	2 @ $\frac{1}{8}$	4.50	0.1934	0.619	3.00	0.0507	0.271	1825
$\frac{5}{8}$ "-S	5	$\frac{3}{16}$	$\frac{3}{16}$	2 @ $\frac{1}{8}$	4.50	0.1670	0.534	3.00	0.0771	0.352	1825
$1\frac{1}{16}$ "-R	5	$\frac{3}{16}$	$\frac{3}{16}$	2 @ $\frac{1}{8}$	5.25	0.2478	0.720	3.00	0.0771	0.352	2000
$1\frac{1}{16}$ "-S	5	$\frac{1}{8}$	$\frac{1}{8}$	2 @ $\frac{3}{16}$	3.75	0.202	0.588	4.50	0.123	0.492	2000
$\frac{3}{4}$ "-R	5	$\frac{1}{8}$	$\frac{1}{8}$	2 @ $\frac{3}{16}$	4.50	0.299	0.798	4.50	0.123	0.492	2225
$\frac{3}{4}$ "-S	5	$\frac{3}{16}$	$\frac{3}{16}$	2 @ $\frac{3}{16}$	4.50	0.251	0.670	4.50	0.171	0.608	2225
$\frac{3}{4}$ "-S	7	$\frac{1}{8}$	$\frac{1}{8}$	3 @ $\frac{1}{8}$	4.50	0.286	0.763	4.50	0.136	0.503	2275
$1\frac{1}{16}$ "-R	7	$\frac{1}{8}$	$\frac{1}{8}$	2 @ $\frac{1}{12}$	5.25	0.365	0.898	4.50	0.171	0.608	2375
$1\frac{1}{16}$ "-R	7	$\frac{1}{8}$	$\frac{1}{8}$	3 @ $\frac{1}{8}$	5.25	0.401	0.988	4.50	0.136	0.503	2375
$1\frac{1}{16}$ "-S	7	$\frac{1}{8}$	$\frac{1}{8}$	3 @ $\frac{1}{8}$	5.25	0.343	0.845	4.50	0.193	0.617	2375
$\frac{7}{8}$ "-R	7	$\frac{1}{8}$	$\frac{1}{8}$	3 @ $\frac{1}{8}$	6.00	0.477	1.090	4.50	0.193	0.617	2600
$\frac{7}{8}$ "-S	7	$\frac{1}{8}$	$\frac{1}{8}$	3 @ $\frac{1}{8}$	6.00	0.427	0.976	4.50	0.243	0.707	2600
$1\frac{1}{16}$ "-R	7	$\frac{1}{8}$	$\frac{1}{8}$	3 @ $\frac{1}{8}$	6.75	0.581	1.241	4.50	0.243	0.707	2800
$1\frac{1}{16}$ "-S	7	$\frac{1}{8}$	$\frac{1}{8}$	3 @ $\frac{1}{8}$	6.75	0.525	1.120	4.50	0.299	0.797	2800
1"-R	7	$\frac{1}{8}$	$\frac{1}{8}$	3 @ $\frac{1}{8}$	7.50	0.701	1.402	4.50	0.299	0.797	3000
1"-S	7	$\frac{1}{8}$	$\frac{1}{8}$	3 @ $\frac{3}{16}$	5.25	0.540	1.080	6.75	0.460	1.131	3000
$1\frac{1}{16}$ "-R	7	$\frac{1}{8}$	$\frac{1}{8}$	3 @ $\frac{3}{16}$	6.00	0.740	1.393	6.75	0.460	1.131	3175
$1\frac{1}{16}$ "-S	7	$\frac{1}{8}$	$\frac{1}{8}$	3 @ $\frac{3}{16}$	6.00	0.615	1.157	6.75	0.585	1.305	3175
$1\frac{1}{8}$ "-R	7	$\frac{1}{8}$	$\frac{1}{8}$	3 @ $\frac{3}{16}$	6.75	0.839	1.490	6.75	0.585	1.305	3350
$1\frac{1}{8}$ "-S	7	$\frac{1}{8}$	$\frac{1}{8}$	3 @ $\frac{3}{16}$	6.75	0.771	1.371	6.75	0.653	1.395	3350
$1\frac{3}{16}$ "-R	7	$\frac{1}{8}$	$\frac{1}{8}$	3 @ $\frac{3}{16}$	7.50	1.022	1.725	6.75	0.653	1.395	3525
$1\frac{3}{16}$ "-S	7	$\frac{1}{8}$	$\frac{1}{8}$	3 @ $\frac{3}{16}$	7.50	0.912	1.538	6.75	0.763	1.526	3525

\* Rough. † Sanded. ‡ Refers to direction of face grain. § For sanded panels, thickness is before sanding.

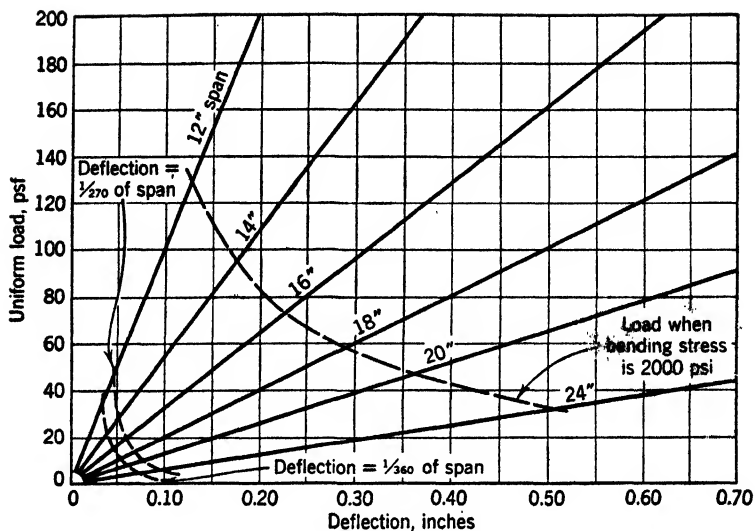


FIG. 4-5. Deflection of Douglas Fir Plywood,  $\frac{1}{4}$ " 3-Ply, Sanded. Simple beam with grain of face plies parallel to span. When grain of face plies is perpendicular to span, take 15 per cent of load on the chart.

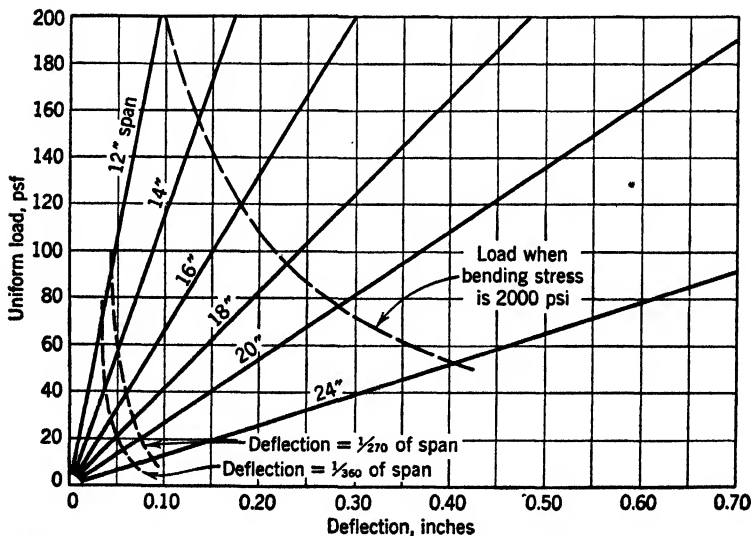


FIG. 4-6. Deflection of Douglas Fir Plywood,  $\frac{5}{16}$ " 3-Ply, Rough. Simple beam with grain of face plies parallel to span. When grain of face plies is perpendicular to span, take 9 per cent of load on the chart.

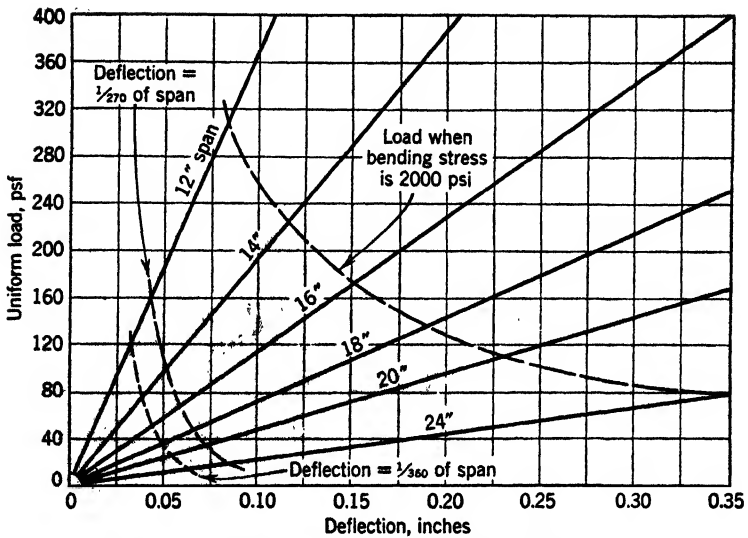


FIG. 4-7. Deflection of Douglas Fir Plywood,  $\frac{3}{8}$ " 3-Ply Rough. Simple beam with grain of face plies parallel to span. When grain of face plies is perpendicular to span, take 9 per cent of load on the chart.

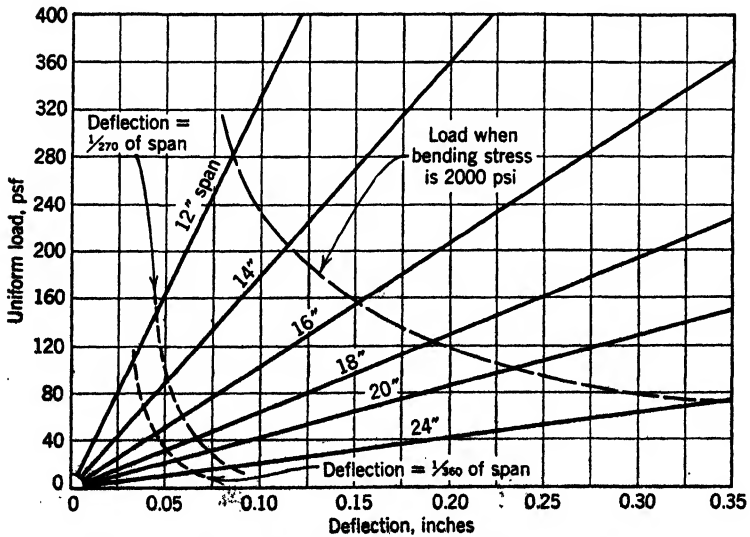


FIG. 4-8. Deflection of Douglas Fir Plywood,  $\frac{3}{8}$ " 3-Ply Sanded. Simple beam with grain of face plies parallel to span. When grain of face plies is perpendicular to span, take 19 per cent of load on the chart.



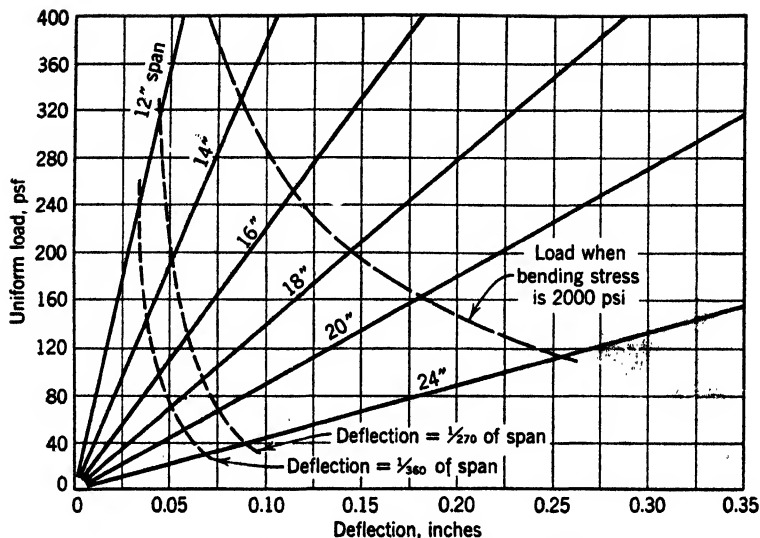


FIG. 4-9. Deflection of Douglas Fir Plywood,  $\frac{1}{2}$ " 5-Ply Rough. Simple beam with grain of face plies parallel to span. When grain of face plies is perpendicular to span, take 31 per cent of load on the chart.

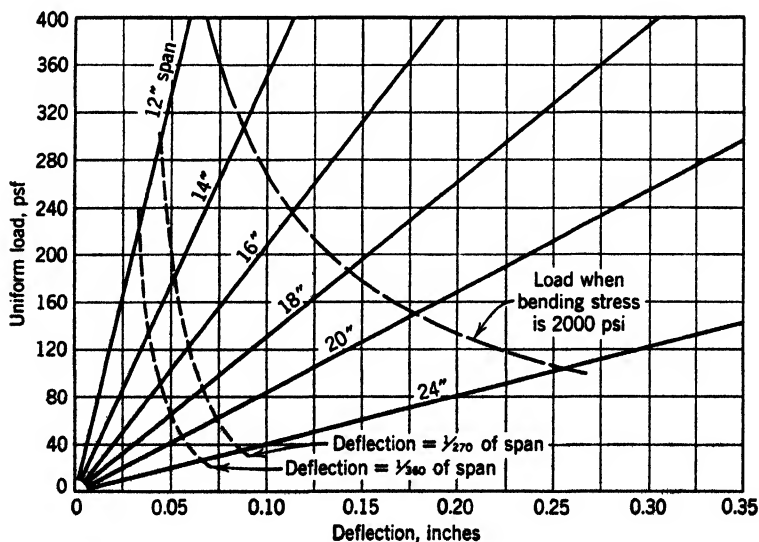


FIG. 4-10. Deflection of Douglas Fir Plywood,  $\frac{1}{2}$ " 5-Ply Sanded. Simple beam with grain of face plies parallel to span. When grain of face plies is perpendicular to span, take 40 per cent of load on the chart.

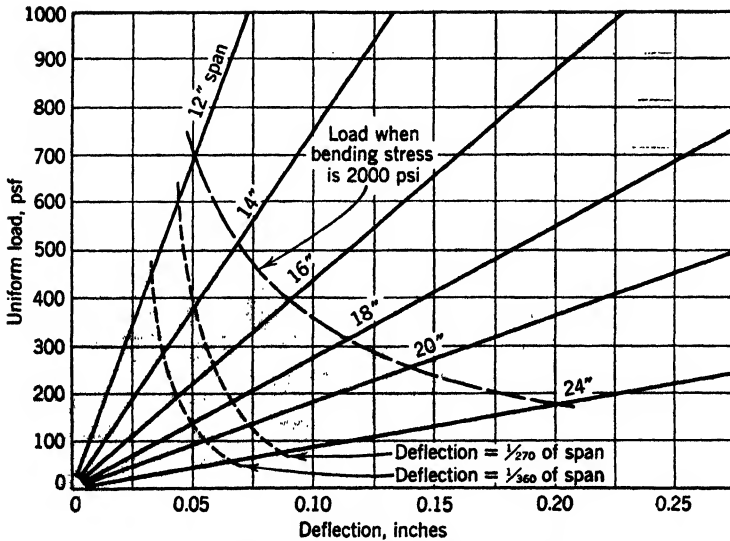


FIG. 4-11. Deflection of Douglas Fir Plywood,  $\frac{5}{8}$ " 5-Ply Rough. Simple beam with grain of face plies parallel to span. When grain of face plies is perpendicular to span, take 31 per cent of load on the chart.

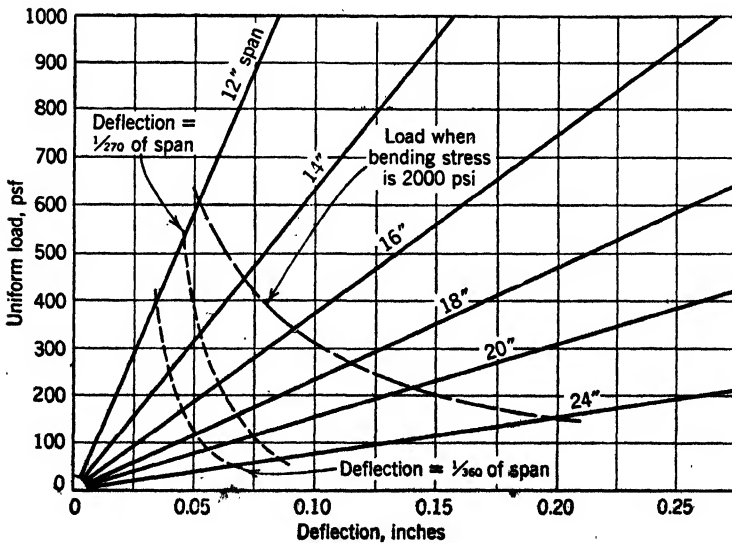


FIG. 4-12. Deflection of Douglas Fir Plywood,  $\frac{5}{8}$ " 5-Ply Sanded. Simple beam with grain of face plies parallel to span. When grain of face plies is perpendicular to span, take 51 per cent of load on the chart.

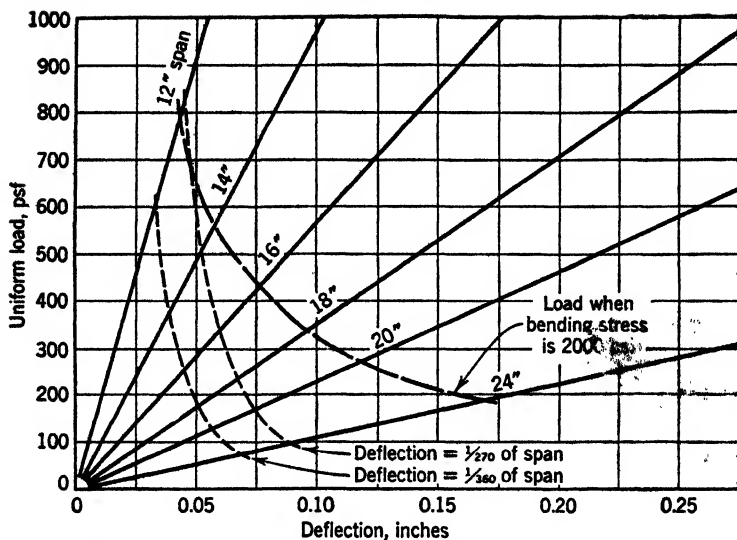


FIG. 4-13. Deflection of Douglas Fir Plywood,  $\frac{5}{8}$ " 5-Ply Sanded. Simple beam with grain of face plies parallel to span. When grain of face plies is perpendicular to span, take 73 per cent of load on the chart.

### CONCRETE FORMS

In concrete form work, tests show that moisture from the concrete causes an increase of about 20 per cent in the deflection of plywood. This means that for plywood forms over three or more supports, the allowable load for any deflection instead of being twice that shown on charts is twice  $\frac{100}{120}$  or 1.67 times as great.

### STRESS CURVE

On each chart is a curve showing loads and deflections when the flexural stress in the plywood is 2000 psi. The factor of 0.85 mentioned in Forest Products Laboratory reprint, Table 4-1, "Load in Bending," page 212 has been included in this curve. This will serve as a guide to the designer, although deflection usually governs in plywood form work. Similarly curves are shown to indicate loads when the deflections are  $\frac{1}{270}$  and  $\frac{1}{360}$  of the span.

### DESIGN OF FLAT PANELS WITH STRESSED COVERS

#### DEFINITION

A panel with stressed covers or simply a "stressed-skin panel" is one in which the covering acts integrally with the framing members to resist

bending stresses in proportion to its effective moment of inertia. It usually consists of several longitudinal framing members, separated by headers, and covered top and bottom with plywood panels.

Such construction is widely used in the prefabrication of houses and other structures and appears to be increasing in importance.

#### LIMITATIONS

1. The covers must be glued to both edges of the framing members in order to develop shear between the framing and the covers.
2. The covers and longitudinal framing members must be continuous in a longitudinal direction or adequately spliced.
3. The covers should be adequate to resist secondary bending stresses from anticipated loads between longitudinal framing members.
4. Headers should be provided whenever relatively thin deep longitudinal members are used.
5. The clear distance between longitudinal members for at least one cover must be less than twice the "basic spacing" calculated as described under Table 4-6.

#### DESIGN

The design of stressed-skin panels follows standard engineering procedure, except that provision must be made to avert buckling under

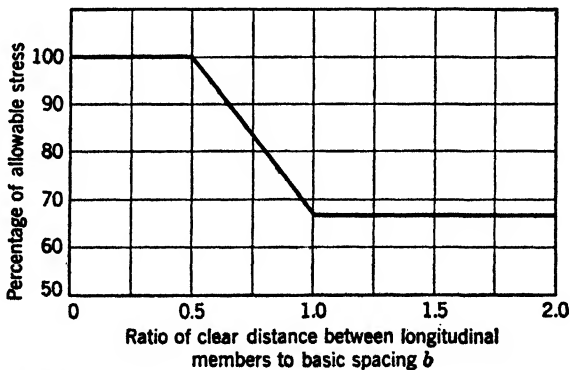


FIG. 4-14. Variation of Allowable Stress with Spacing of Framing Members.

high loads. This is done in accordance with methods suggested in a bulletin prepared by John Newlin and issued in 1940 by the U. S. Forest Products Laboratory following an extensive test program.

The procedure involves a simple calculation of a "basic spacing" for longitudinal framing members, using formulas given below. In com-

puting the moment of inertia of the panel, or of an I section consisting of one framing member and its contributing stressed-cover area, the effective width of the covers or flanges may not exceed the basic spacing,  $b$ . Also, if the actual clear distance between framing members exceeds  $b/2$ , the allowable stresses in bending (on tension face) and in compression parallel (on compression face) are reduced as shown in Fig. 4-14.

Special attention must be given to horizontal shear in such built-up panels because the critical shear usually occurs in the plane of the plies, as illustrated in Fig. 4-4, when only a relatively low shear stress is recommended. It is apparent therefore that the allowable panel load may be governed by the width of the framing members.

#### CALCULATION

A. The design may be based either on the entire width of panel or an I section consisting of one framing member and its contributing cover area. Although the procedure is similar in both cases, it is simpler and ordinarily sufficiently accurate to use the latter method, as described in the following paragraphs.

B. Determine the basic spacing  $b$  for top and bottom covers from Table 4-6, page 232, using appropriate grain direction.

C. Locate the neutral axis of the I section by taking moments about some convenient point. Consider the cover width as extending halfway to the adjacent framing members, unless the clear distance between members exceeds  $b$ , in which case take the cover width equal to  $b$  plus the framing member thickness. Also consider only those plies in the covers whose grain is parallel to the span.

D. Find the moment of inertia of the section, considering the material used in locating the neutral axis.

E. Determine the allowable resisting moment of the section on both tension and compression faces, by means of the flexure formula. In each case use the appropriate distance from the neutral axis to the extreme fiber as determined in paragraph C. Use the appropriate stress as found in paragraph F applying the allowable bending stress in the extreme fiber to the tension face and the allowable stress in compression parallel to the compression face. The allowable bending moment on the panel will equal the smaller value of the resisting moment, in tension or compression.

F. Working stresses for Douglas fir plywood are given in Table 4-4. These are suitable for use with stressed-skin panels, *provided* the clear distance between framing members is not greater than  $b/2$ .

When this spacing exceeds  $b/2$ , the recommended working stresses in both bending and compression parallel (but not in rolling shear) must be reduced proportionately from 100 per cent at  $b/2$  to 67 per cent when the clear spacing is  $b$  or greater, as illustrated in Fig. 4-14.

This reduction, as previously mentioned, is to provide against buckling of the covers.

*G.* The deflection under a given load may be calculated by using customary deflection formulas for the appropriate loading condition, employing the moment of inertia from paragraph *D* and the modulus of elasticity for the cover material (1,600,000 psi for Douglas fir plywood).

*H.* The allowable load as determined by rolling shear should be calculated for the interior framing member together with its contributing area of covers, because the critical shearing stress occurs in this region. The allowable shear may be found as follows:

1. Find the statical moment about the neutral axis of those parallel plies outside the critical rolling shear plane. The critical shear plane lies within the plywood between the inner parallel ply and the adjacent perpendicular ply when the plywood cover has its face grain parallel to the longitudinal framing members. When the face grain of the cover is perpendicular to the framing member, the critical rolling shear plane lies between the inner perpendicular ply and the framing member (see Fig. 4-4). The statical moment of the compression side is ordinarily larger, but if the tension side gives a higher value it should be used.

2. The allowable shear may be found from the formula:

$$V = sIt/Q$$

where  $V$  = allowable external shear on section, lb

$s$  = allowable rolling shear stress, psi

$I$  = moment of inertia of the section, in.<sup>4</sup>

$t$  = thickness of longitudinal member, in. (The stress will be concentrated above the framing member, even though the plane may occur within the plywood itself.)

$Q$  = statical moment of the *parallel* plies outside the critical shear plane, in.<sup>3</sup>

The allowable shear load on the section should then be checked against the allowable bending load on the panel. The smaller value will determine the working load.

*I.* If desired, the allowable load as determined by horizontal shear at the neutral axis may be found from the formula:

$$V' = s'It/Q'$$

where  $V'$  = allowable external shear on section, lb

$s'$  = allowable horizontal shear stress, psi, for the species and grade of the framing member

$Q'$  = statical moment about the neutral axis of all parallel grain material above (or below) the neutral axis

$I$  and  $t$  have the same meaning as in paragraph 2.

TABLE 4-6. BASIC SPACING  $b$  FOR VARIOUS PLYWOOD THICKNESSES

For Use in Calculating the Strength of Stressed-Skin Panels

For three-ply plywood $b = 31h$	$\sqrt{\frac{h}{\text{total thickness of parallel plies}}}$
For five or more plies $b = 36h$	$\sqrt{\frac{h}{\text{total thickness of parallel plies}}}$

where  $h$  is the thickness of the plywood (see Table 4-5, page 222).

Plywood Thickness, in.	Basic Spacing $b$ , in.	
	Face Grain Parallel to Longitudinal Members	Face Grain Perpendicular to Longitudinal Members
$\frac{1}{4}$ sanded	10.35	11.61
$\frac{5}{16}$ rough	11.87	16.80
$\frac{3}{8}$ rough (3-ply)	14.25	20.13
$\frac{3}{8}$ sanded (3-ply)	16.43	16.43
$\frac{3}{8}$ sanded (5-ply)	18.10	20.25
$\frac{1}{2}$ rough and sanded	23.25	28.5
$\frac{5}{8}$ rough and sanded	29.1	35.6
$\frac{3}{4}$ sanded (5-ply and 7-ply)	38.2	38.2
$\frac{7}{8}$ rough and sanded	41.6	48.1
1 rough	45.5	58.9
1 sanded	54.5	47.9

#### SAMPLE CALCULATION OF A STRESSED-SKIN PANEL

Suppose it is required to check the bending strength of the 4-ft-by-8-ft floor panel shown in Fig. 4-15 when supported on a 7-ft 9-in. span.

##### 1. Basic Spacing (From Table 4-6):

$$\text{Top: } b = 23.25 \text{ in.} < 11.06 \text{ in.}$$

$$\text{Bottom: } b = 10.35 \text{ in.} < 11.06 \text{ in.}$$

## Sample Calculation of a Stressed-Skin Panel 233

∴ Consider the top cover to be clear distance between joists plus joist thickness = 11.06 in. + 0.75 in. = 11.81 in. Consider bottom cover as  $b$  plus joist thickness = 10.35 in. + 0.75 in. = 11.10 in.

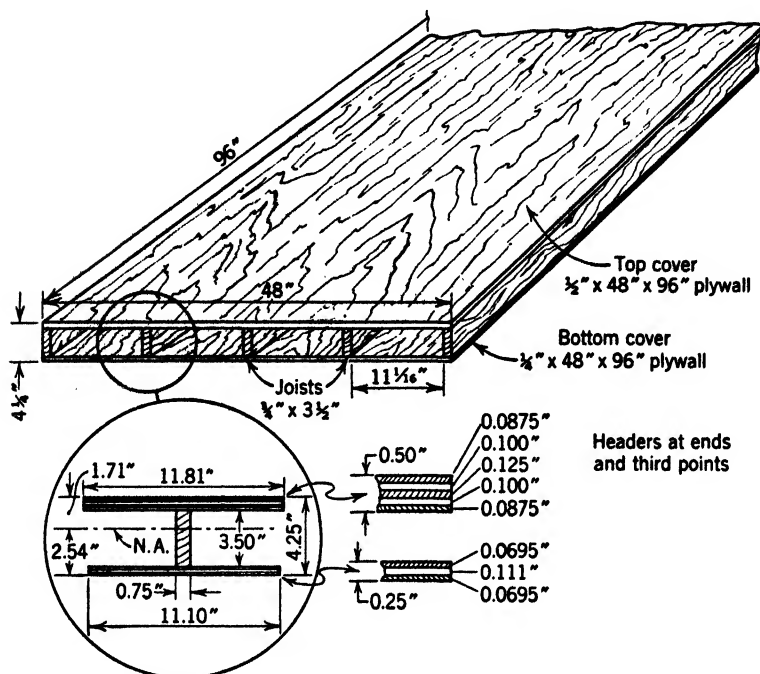


FIG. 4-15. Stressed-Cover Analysis.

### 2. Neutral Axis. Moments about base (neglect perpendicular plies).

	Area, in. <sup>2</sup>	Moment, in. <sup>3</sup>
Bottom: (0.139)(11.10)	$1.542 \times 1.25 =$	0.19
Joist: (0.75)(3.5)	$2.625 \times 2.00 =$	5.25
Top: (0.30)(11.81)	$3.543 \times 4.00 =$	14.17
	<hr/> 7.710	<hr/> 19.61

$$\text{N.A. lies } \frac{19.61}{7.71} = 2.54 \text{ in. above base.}$$

**3. Moment of Inertia.** The moment of inertia of the covers is most readily found from the parallel-axis formula  $I = I_o + Ad^2$ ; that of



the joist by using the formula for the moment of inertia of a rectangle about an axis through its base,  $I = bd^3/3$ . Moments of inertia of the covers about their own axes are listed on page 222, Table 4-5.

$$\text{Bottom: } \frac{11.10}{12} (0.0143) + 1.542(2.415)^2 = 9.00$$

$$\text{Joist: } \frac{(0.75)(1.21^3 + 2.29^3)}{3} = 3.45$$

$$\text{Top: } \frac{11.81}{12} (0.0926) + 3.543(1.46)^2 = 7.65$$

$$\therefore I_g \text{ for one I-beam section} = 20.10 \text{ in.}^4$$

**4. Allowable Stresses (Dry Location).** Top: The recommended working stress for 5-ply Plywall\* grade in compression parallel is 1375 psi.

Ratio of actual spacing to basic spacing is  $\frac{11.06}{23.25} = 0.475$  which is less than  $\frac{1}{2}$ .

$\therefore$  Use full allowable stress of 1375 psi.

Bottom: Recommended stress for Plywall grade in bending is 2000 psi

Ratio of actual spacing to basic spacing is  $\frac{11.06}{10.35} = 1.07$ .

$\therefore$  Reduce allowable stress to 67% =  $(0.67)(2000) = 1340$  psi.

**5. Allowable Load (Based on Flexure).** Resisting moments:

$$\text{Top: } M = \frac{sI}{c} = \frac{1375(20.1)}{1.71} = 16,160 \text{ in.-lb}$$

$$\text{Bottom: } M = \frac{1340(20.1)}{2.54} = 10,600 \text{ in.-lb}$$

$\therefore$  Tension governs, and allowable uniform load on 7-ft 9-in. span is

$$w = \frac{8(10,600)}{93(7.75)} \times \frac{12}{11.81} = 119.2 \text{ psf.}$$

**6. Rolling Shear.** Statical moment of upper panel is computed for the two upper plies only, because when the face grain of the plywood is parallel to the joist, as in this case, the critical rolling shear plane falls within the plywood, between the lower parallel and perpendicular plies.

\* This grade obsolete since 1947.

## Sample Calculation of a Stressed-Skin Panel 235

$$Q = (0.2125)(11.81)(1.55) = 3.89 \text{ in.}^3$$

Allowable shear on panel (determined by rolling shear stress of 48 psi for Plywall grade).

$$V = \frac{sIt}{Q} = \frac{48(20.1)(0.75)}{3.89} = 186 \text{ lb}$$

Allowable load to cause shear of 186 lb =

$$\frac{2(186)}{7.75} \times \frac{12}{11.81} = 48.7 \text{ psf}$$

**7. Horizontal Shear.** Horizontal shear stresses in the joists at the neutral axis are usually so low as not to require checking, but they have been computed in this case as an example.

Statical moment of all parallel grain material above the neutral axis:

$$Q' = 3.543(1.46) + \frac{1.21^2}{2} (0.75) = 5.73 \text{ in.}^3$$

Allowable shear on panel (governed by an assumed shear working stress of 100 psi)

$$V' = \frac{100(20.1)(0.75)}{5.73} = 264 \text{ lb}$$

$$\text{Allowable load to cause shear of 264 lb} = \frac{2(264)}{7.75} \times \frac{12}{11.81} = 69.3 \text{ psf.}$$

**8. Deflection.** (a) The uniform load required to cause a deflection of  $\frac{1}{360}$  of the span is found from the usual deflection formula.

$$d = \frac{93 \text{ in.}}{360} = \frac{5}{384} \frac{Wl^3}{EI} = 0.258 \text{ in.}$$

The value of  $E$  is taken as that of the covers, and is 1,600,000 psi for Douglas fir plywood, regardless of grade and location.

$$W = \frac{384(1.6 \times 10^6)(20.1)(0.258)}{5(93^3)} = 793 \text{ lb}$$

where  $W$  = load on I section, 11.81 in. wide and 7 ft 9 in. long.

$$\therefore w = \frac{793}{7.75} \times \frac{12}{11.81} = 104 \text{ psf}$$

(b) The load required to cause a deflection of the top cover only of  $\frac{1}{360}$  of the span between joists may be found from the deflection chart, Fig. 4-10. Taking the joists at 12 in. centers, and noting that the grain of the face plies is perpendicular to the span, it can be seen that the continuous beam load to cause a deflection of  $\frac{1}{360}$  of the span is  $2(215)(0.40) = 172$  psf.

Conclusion. It is apparent that the design load of the panel, 48.7 psf could be increased appreciably by using a thicker joist.

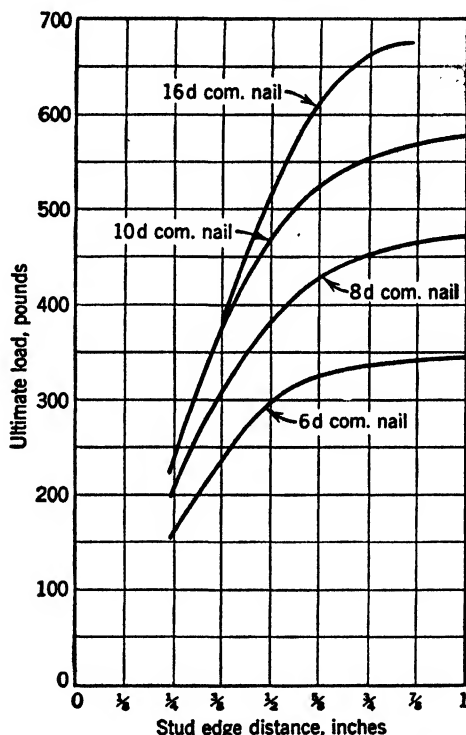


FIG. 4-16. Ultimate Loads on Nails versus Stud-Edge Distances. All studs of Douglas fir.

#### LATERAL BEARING STRENGTH OF NAILED PLYWOOD JOINTS

When plywood acts as a bracing diaphragm nailed over wood framing, as in walls, roofs, and floors, subjected to wind or earthquake loads, the shear stress that can be developed in the plywood will usually be limited by the stresses transferred through the lateral bearing of the nails against the plywood and the wood framing.

This bearing value may be limited by the distance of the nail from the edge of both the plywood and the framing members, particularly with studs 2 in. or less in thickness. The bearing will be affected also, of course, by the plywood thickness, nail size, and lumber species.

A series of tests to determine these lateral nail-bearing values using several common thicknesses of plywood and sizes of nails was conducted in the Douglas Fir Plywood Association laboratory.

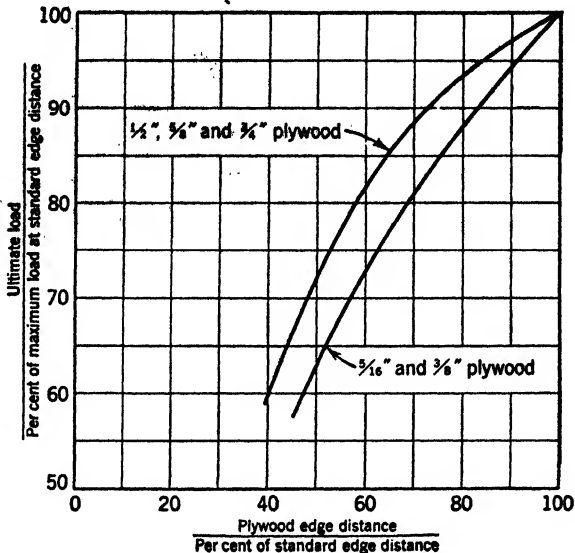


Fig. 4-17. Ultimate Loads on Nails versus Plywood-Edge Distances.

The framing members, hereafter referred to as the studs, were of Douglas fir, with moisture contents varying from 11 to 20 per cent. Joints were loaded parallel, perpendicular, and at 45° to the face-ply grain of the plywood, although no consistent difference showed up in this respect.

In order to develop the maximum bearing value of a nail in a stud it is necessary to have a certain minimum distance from the center of the nail to the edge of the stud, in the direction of the applied load. These minimum edge distances for maximum bearing values were determined for four nail sizes on representative Douglas fir studs; also the lesser load values for reduced edge distances. These data are presented in Fig. 4-16.

In a similar manner the maximum bearing loads were determined for the common combinations of nails and plywood thicknesses, as well as

the loads at reduced edge distances. It was found that as the edge distance was decreased from that required to develop the maximum load, the strength was reduced by a definite percentage depending on the number of plies. These data are shown in Fig. 4-17 and in Table 4-7.

TABLE 4-7. ULTIMATE LOADS AT STANDARD PLYWOOD EDGE DISTANCES FOR  
LATERALLY LOADED NAIL JOINTS

For Stud Edge Distances 1 in. or Greater

Plywood Thickness, in.	Nail Size							
	6d Common		8d Common		10d Common		16d Common	
	Load, lb	Plywood Edge Distance, in.	Load, lb	Plywood Edge Distance, in.	Load, lb	Plywood Edge Distance, in.	Load, lb	Plywood Edge Distance, in.
$\frac{3}{16}$	335	$\frac{1}{2}$	420	$\frac{5}{8}$				
$\frac{3}{8}$	345	$\frac{1}{2}$	470	$\frac{5}{8}$				
$\frac{1}{2}$			470	$\frac{5}{8}$	500	$\frac{1}{2}$		
$\frac{5}{8}$			470	$\frac{5}{8}$	575	$\frac{5}{8}$	620	$\frac{5}{8}$
$\frac{3}{4}$					575	$\frac{3}{4}$	675	$\frac{3}{4}$

Table 4-7 gives the maximum loads and the plywood edge distances required to develop them. Figure 4-17 shows the variation of loads with edge distances for three-ply and five-ply plywood. The loads are plotted as a percentage of the maximum loads, and the edge distances as a percentage of the edge distance required to develop these maximum loads.

In the majority of cases when plywood is nailed to framing members, the available edge distances at the panel edges were usually insufficient to develop the maximum loads given in Table 4-7; however, the reduced loads may be found by using the data of Figs. 4-16 and 4-17.

For example, if two  $\frac{1}{2}$ -in. plywood panels are butted over the center line of a  $1\frac{5}{8}$ -in. stud, only half this thickness or  $1\frac{3}{16}$  in. is available to each panel for nailing. If 8d common nails are driven  $\frac{3}{8}$  in. from the plywood edge, the stud edge distance will be  $\frac{7}{16}$  in. Figure 4-16 shows the stud bearing value at  $\frac{7}{16}$  in. to be 350 lb. Table 4-7 shows a maximum load of 470 lb at a  $\frac{5}{8}$ -in. edge distance for the plywood. Since the available edge distance is only  $\frac{3}{8}$  in., or 60 per cent of that required for maximum load, it may be seen from Fig. 4-17 that the ply-

wood bearing value is 82 per cent of 470 lb or 385 lb. Thus the stud bearing value of 350 lb determines the strength of this joint.

For convenience Table 4-8 has been worked out to show the ultimate loads of plywood panels butted on the center lines of 1 $\frac{5}{8}$ -in. Douglas fir studs. Edge distances have been chosen so that maximum joint strength will result. A suitable factor of safety should be applied to the tabular values.

TABLE 4-8. MAXIMUM ULTIMATE LOADS OF PLYWOOD NAILED TO 1 $\frac{5}{8}$ -IN. DOUGLAS FIR LUMBER

Plywood Panels Butted at the Center Lines of Studs  
Any change in edge distance will decrease load.

Plywood Thickness, in.	Nail Size							
	6d Common		8d Common		10d Common		16d Common	
	Load, lb	Plywood Edge Distance, in.	Load, lb	Plywood Edge Distance, in.	Load, lb	Plywood Edge Distance, in.	Load, lb	Plywood Edge Distance, in.
$\frac{1}{8}$	275	$\frac{3}{4}$	305	$\frac{3}{4}$				
$\frac{3}{8}$	275	$\frac{3}{4}$	340	$\frac{3}{4}$				
$\frac{1}{2}$			350	$\frac{3}{4}$	425	$\frac{3}{4}$		
$\frac{5}{8}$			350	$\frac{3}{4}$	425	$\frac{3}{4}$	445	$\frac{3}{4}$
$\frac{3}{4}$					410	$\frac{3}{4}$	445	$\frac{3}{4}$

The translation of the actual ultimate loads given in Table 4-8 to safe working loads should be largely a matter of judgment for the individual designer. Some of the factors which may enter into consideration are:

1. *Proportional Limit.* Working loads should not exceed the proportional limit, which is about 25 to 30 per cent of the ultimate. (A nailed joint does not show a true proportional limit, but rather a region in which the rate of deformation with respect to the load increases rapidly.)

2. *Variability.* The nailing properties of Douglas fir are subject to a variation of about 25 per cent above and below the average. It is conservative to design for the weakest case.

3. *Seasoning.* Limited tests indicate a loss of about 25 per cent in strength when the joint is subject to moisture-content changes. When exposure is severe, the loss may be even greater.

4. *Load Application.* When the joint is subjected to loading over a period of years, its strength is probably decreased in the same way that a wooden beam is affected. The long-time loading strength of such a member is taken as  $\frac{9}{16}$  of the short-time test load. Also load repetition and reversal may act to reduce the joint strength.

When the working load is not otherwise specified by the building code, it is suggested that the ultimate values be divided by a factor of four or five to obtain safe loads.

The values given in Fig. 4-16 should be modified when the stud material is other than Douglas fir. The U. S. Forest Products Laboratory's *Wood Handbook* gives data on this subject on page 123.

## THE DESIGN OF BUILT-UP BEAMS WITH PLYWOOD WEBS

### INTRODUCTION

This section outlines a method of designing plywood beams to withstand given loads with adequate safety factors. For convenience in the following discussion the term "plywood beams" will be used to designate built-up wood beams having plywood webs.

### DESCRIPTION

Plywood beams generally consist of one or more vertical plywood webs to which lumber flanges are glued along the top and bottom edges. At intervals along the beam vertical lumber stiffeners separate the top and bottom flanges. In the following discussion all plywood design values given are those for Douglas fir. Any species of wood may be employed for the lumber flanges but practical considerations usually limit the choice to those commonly available in structural grades.

Although there is no definite limitation on the span length which may be bridged with plywood beams, the economical limit appears to be about 60 ft. The beam depth is limited by the plywood panel size available.

The shape may be an I beam with a single web and flanges top and bottom, or it may include any number of webs separated by flanges, the outer layers being either webs or flanges, in which case the assembly is generally called a box beam. In either case, the design procedure is similar.

### APPLICATIONS

Plywood beams have been used in frame buildings as floor and roof girders. The principal advantages of plywood beams are that they

require a minimum of material and are consequently light in weight. Because the unit is dry when fabricated, and the plywood itself imparts a considerable degree of dimensional stability, difficulties from sagging and shrinkage are reduced, and maintenance such as bolt tightening is minimized.

#### CHOICE OF SECTION

The design of a plywood beam yields readily to ordinary engineering analysis although the usual formulas are modified slightly in certain respects. Knowing the span and loads, it is possible to select a trial cross section, as shown subsequently. This trial section may then be checked for flexure, horizontal shear, shear between flange and web, and deflection. Design of splices and location of vertical stiffeners and lateral supports may also be checked. If the member has a variable cross section, each section should be investigated. Obviously the form and dimensions of the members should be such that it can be built with available facilities. For the shorter spans and lighter loads an I beam may be used. However, unless thick plywood is obtainable, a box section will generally be more suitable. Other designs utilize a variable cross section along the built-up beam.

The economic advantages of this generally become more apparent as the span increases, particularly beyond the commonly available lengths of lumber. Flanges can be built up of several pieces so as to vary the amount of material to conform with the bending moments. Longer spans also provide a better chance to alter the number of webs so as to conform with the varying shear requirements. In addition, the depth of the beam may be varied to produce a curved upper surface—often desirable for roof drainage—or camber in the lower flange.

#### GLUING

All joints between lumber and plywood can be made satisfactorily with glue if proper technique and materials are employed. Approximately the full strength of wood parallel to the grain can be developed with glued end-grain scarf joints, whereas glued side-grain butt joints are sufficient to develop the full strength perpendicular to the grain.

A number of high-grade assembly glues are available today, but they should be used in strict accordance with manufacturers' directions, and with special attention to pressure, temperatures, assembly times, and spread. Fully as important are moisture content and surfacing of lumber, method of applying pressure, and conditions of cure. Hydraulic presses and clamps are commonly used in modern shop gluing.



A variation of this technique which has been practiced to some extent is nail gluing. With this method the beam is ordinarily built on or near the site, nails being used to provide pressure for setting the glue. This method permits less accurate control in many respects than shop fabrication, owing partly to the presence of butt joints in the flanges, but chiefly to uncertainty as to pressures obtained with nails.

It is customary to design with individual laminas which are fairly thin—usually 1 in. or 2 in.—because of the necessity of using uniformly dry lumber and the requirements of sufficient flexibility for intimate contact at the glue line between adjacent members.

### DESIGN METHOD

#### TRIAL CROSS SECTION

After deciding on the type of beam and the method of manufacture, the next step is to select a preliminary cross section. The depth may be found by selecting an arbitrary span-depth ratio, ranging, probably, from 6 to 12. It is ordinarily economical to select a depth equal to a stock width of plywood in order to reduce cutting and waste.

Next, the required web thickness at a given section may be determined approximately from the formula,

$$t = \frac{1.25V}{hv} \quad (4-1)$$

where  $t$  = total web thickness, in.

$V$  = shear at the section, lb

$h$  = beam depth at the section, in.

$v$  = allowable plywood shear stress perpendicular to the plane of the plies, psi

The value of  $t$  thus found is useful in a preliminary design, but it should be tempered by a consideration of the available plywood thicknesses and of the number of contact surfaces necessary to develop the flange-web shear.

The approximate minimum flange depth required at the section of maximum shear will generally be about six times the thickness of the adjoining web if the web has a flange glued to it on only one side, or three times the web thickness if there are two flange faces as in an I beam. These approximate flange depths are those required by the allowable shear on a glued joint; they do not necessarily indicate a desirable depth at the section of maximum bending moment.

The next step is to ascertain the moment of inertia requirements, using the standard flexure formula (modified by a form factor as discussed in the following paragraph), giving the equation,

$$I = \frac{Mc}{Ff} \quad (4-2)$$

where  $I$  = the *net* moment of inertia, in.<sup>4</sup>, of the total section neglecting any flange laminations which are butt-jointed at the given section, and those plies in the web having their grain perpendicular to the span

$M$  = the bending moment at the section, in.-lb

$c$  = distance from the neutral axis to the extreme fiber, in.

$F$  = form factor, assumed as 0.80 for preliminary purposes

$f$  = allowable fiber stress in bending of the flange lumber, psi

The allowable deflection is computed by using the *average gross* moment of inertia. The gross moment of inertia includes all fibers, regardless of butt joints, whose grain is parallel to the span. If the cross section is variable along the span, the moment of inertia thus found will be the average effective  $I$  for the entire beam. The customary deflection formulas may be employed, but a factor should be added to provide for the effect of shearing deflection, which is not negligible in built-up plywood beams. Again for preliminary purposes only, it will be sufficiently accurate to add 25 per cent to the deflection as calculated from the customary formulas.

When  $I$  has been determined, the flange requirements may be estimated by subtracting the  $I$  of the webs at the section in question. The flanges may be made up from standard lumber sizes, but allowance should be made for possible resurfacing which will reduce the thickness of the individual pieces after scarfing and the width or depth of the flanges before they are glued to the web.

## ACCURATE DESIGN CHECK

The sections obtained so far are purely for trial purposes. Formulas suggested are only approximations, to fit average conditions. The design should not be considered satisfactory until the sections have been inspected by the methods outlined in the following paragraphs.

### 1. Flexure

Values of the moment of inertia and of the form factor should be computed from the actual net dimensions.

In computing the net  $I$  it should be reiterated that only those plies in the web having their grain parallel to the span are considered. Any openings in the flange, such as butt joints, near the section in question, should be omitted in calculations of the net moment of inertia. How-

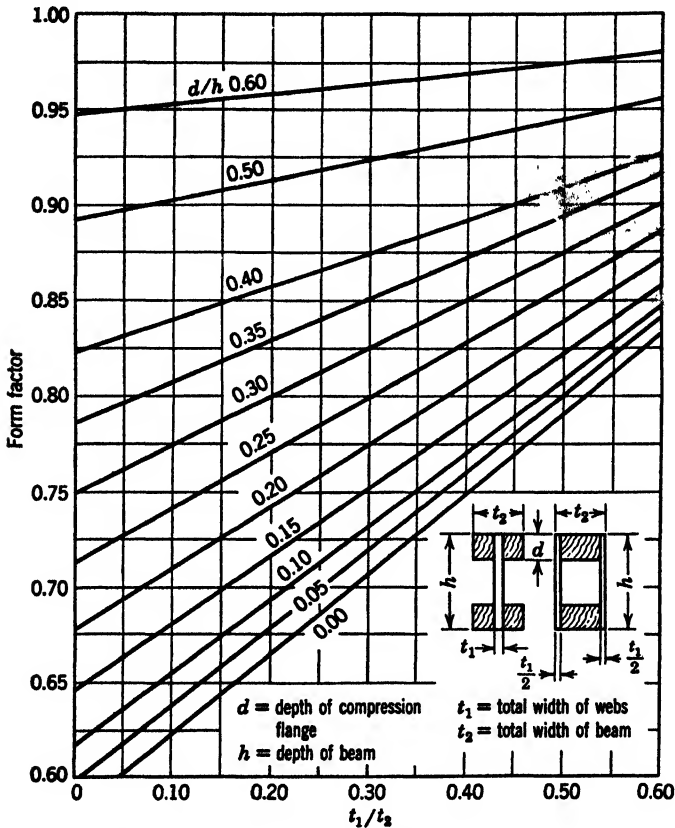


FIG. 4-18. Form Factor of Plywood Beams.

ever, the location of the neutral axis is determined by the gross section; exclusive of perpendicular grain material, and is not affected by local irregularities such as butt joints. Thus the bending stresses will be calculated with the *net* moment of inertia and the distance of the fiber from the neutral axis of the *gross* section.

Values of the form factor, which depend on the relative dimensions of the section, may be taken from Fig. 4-18. This chart, based on data published by the U. S. Forest Products Laboratory, is a graphical solution of their equation for the proportional-limit form factor.

The form factor at proportional limit of a built-up plywood beam is the ratio of the fiber stress at the proportional limit of the beam to the similar property of a rectangular-beam 2 in. by 2 in. in cross section and of the same material as in the flanges of the built-up beam; it is less than unity. The reason for its existence may be understood when it is recalled that the stress at proportional limit and at ultimate for wood is less in compression than in bending. It has been suggested that in bending the lower-stressed fibers support the higher-stressed extreme compression fibers, reinforcing them against buckling failure by column action, and enabling them to withstand a compression stress higher than if all fibers were uniformly stressed. In a built-up beam, as compared with a solid beam, some of the supporting fibers are removed, thereby reducing the load-carrying capacity of the extreme fibers. Therefore, as the beam dimensions are altered so that the stress in the compression fibers approaches a uniformly distributed compression stress, the proportional limit and ultimate stress are reduced from that for bending toward that for compression. Since the allowable bending stress is used in plywood beam design, it is evident that some reduction factor should be used to interpolate between pure bending and pure compression stresses.

For the same reason that a form factor is applied to I and box beams, a depth factor is applied to solid rectangular wood beams. In this case, however, the depth factor accounts for the decreasing amount of support as the distance between extreme fiber and lesser-stressed supporting fibers increases. The value of the depth factor is given by the formula,

$$F = 1 - 0.07(\sqrt{d/2} - 1) \quad (4-3)$$

in which  $d$  is the depth of the beam in inches.

It is ordinarily neglected in timber design, because, when working stresses were being derived from tests on 2-in.-by-2-in. test specimens, there was applied an average depth factor of 0.90, corresponding to a 12-in. beam depth. However, the application of a form factor to an I or box beam also takes the depth of the beam into account. For this reason it is recommended that the form factor of an I or box beam be multiplied by 1% before it is applied to the flexure formula. Strictly speaking the 1% correction should be applied to the working stresses, but it is more convenient to consider it with the form factor.

The actual stress existing within either tension or compression flange is given by the equation,

$$s = \frac{Mc}{I} \quad (4-4)$$

whereas the form factor applies *only* to the compression flange. Thus the compression flange will govern the design in a beam that is symmetrical about its neutral axis, while the tension flange will be understressed.

This suggests a possibility for utilizing material more closely, either by reducing the dimensions of the tension flange, as is commonly done in aircraft wing beams, or by using a lower-stress grade of lumber there.

## 2. Horizontal Shear

The horizontal shear stress in the plywood web may be checked at the section of maximum shear by applying the formula,

$$v = \frac{VQ}{It} \quad (4-5)$$

where  $v$  = horizontal (or vertical) shear stress on the plane under consideration (usually the neutral axis), psi

$V$  = total shear on the cross section, lb

$Q$  = statical moment about the neutral axis of all fibers whose grain is parallel to the beam's axis and lying outside the plane under consideration, in.<sup>3</sup>

$I$  = gross moment of inertia of all parallel fibers about the neutral axis, in.<sup>4</sup>

$t$  = total thickness of the plywood webs at the cross-section, in.

It is inaccurate and not on the side of safety to assume that the shearing stress is evenly distributed throughout the depth of the plywood webs, as is done in the case of steel I beams, because the relative proportions of web and flanges are different for beams of the two materials. It is also inaccurate and unduly conservative to use the customary formula for rectangular wooden beams,  $v = 3V/2A$ , as the latter is simply a special case of equation 4-5 and does not apply to webbed beams.

## 3. Flange-Web Shear

Where the flanges and webs are joined by glue, the joint is parallel with the plane of the plies and its strength is limited by rolling shear. The allowable stress is considerably lower for rolling shear—that is, shear in the plane of the plies—than for shear perpendicular to the plane of the plies.

The method for determining the maximum flange-web shear stress is based on the assumption that the horizontal shear stress is equal in all webs and that they therefore receive load from the flanges in proportion to their thickness. Thus in Fig. 4-19A the shear stress on plane *B*

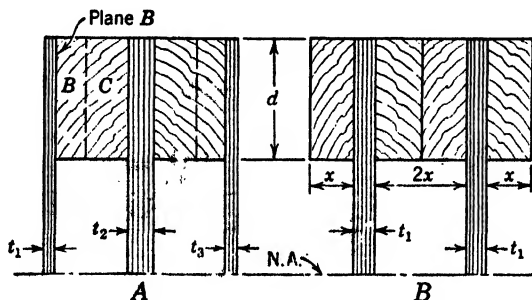


FIG. 4-19. Flange and Web Analysis.

would be  $\frac{t_1}{t_1 + t_2 + t_3}$  times the total flange-web shear. It can be shown that this total shear is

$$s = \frac{VQfl}{Id} \quad (4-6)$$

where  $Qfl$  = the static moment about the neutral axis of the flange under consideration, in.<sup>3</sup>

$d$  = the depth of the flange-web glue joint, in.

A special case exists when the webs are of equal thickness and the flanges of equal depth and so divided as to give an equal stress intensity to each contact face. Such a condition will hold in an I beam or a box beam such as that shown in Fig. 4-19B. In this case the flange-web shear stress is

$$s = \frac{VQfl}{nId} \quad (4-7)$$

where  $n$  is the total number of contact faces between the webs and flanges.

#### 4. Deflection

Plywood girders, if the webs are effectively spliced, will act as a unit and deflect according to elastic theory. Consequently, the usual beam-deflection formulas may be employed. However, these formulas neglect

the effect of shearing deformation which should be calculated and added to the bending deflection.

The amount of shear deflection is affected by the position and intensity of the loads, the span, cross-sectional dimensions, and the shear modulus of the webs. Formulas for computing shear deflection have been worked out theoretically and verified experimentally.<sup>4</sup>

The shear deflection of a section which is symmetrical about its horizontal axis may be expressed by the formula,

$$d_s = \frac{PlKh^2C}{GI} \quad (4-8)$$

where  $d_s$  = shear deflection, in.

$P$  = total load on beam, lb

$l$  = span length, in.

$K$  = a factor determined by the beam cross section, and shown in Fig. 4-20

$h$  = depth of beam, in.

$C$  = a coefficient depending on the manner of loading, also shown in Fig. 4-20

$G$  = shearing modulus of the webs, psi

$I$  = gross moment of inertia of the section, in.<sup>4</sup>

For sections symmetrical about their neutral axis, the factor  $K$  is determined by the same ratios that affect the form factor; that is,  $d/h$ , the ratio of the compression flange depth to the beam depth, and  $t_1/t_2$ , the ratio of the total web thickness to the total beam width.

The shearing modulus of Douglas fir plywood having the face grain either parallel or perpendicular to the span may be taken as 117,000 psi at 15 per cent moisture content. If the face grain is at 45° to the span, a value of 375,000 psi corresponds to a 15 per cent moisture content, according to information issued by the Forest Products Laboratory.

If the cross section of the beam varies along its length, the dimensions used for calculating the factor  $K$ , as well as the depth and moment of inertia in the shear-deflection formula should be those of the sections subjected to shear, weighted with respect to the area of the shear diagram. For instance if third-point loading is used, the calculations are made for the average cross section in the outer thirds.

If a beam is subjected to two loadings simultaneously—for example, a uniform and a concentrated load—the shear deflection for each loading condition may be computed separately and added.

In computing the deflection caused by bending, the true modulus of elasticity of the flange species should be used in the ordinary deflection

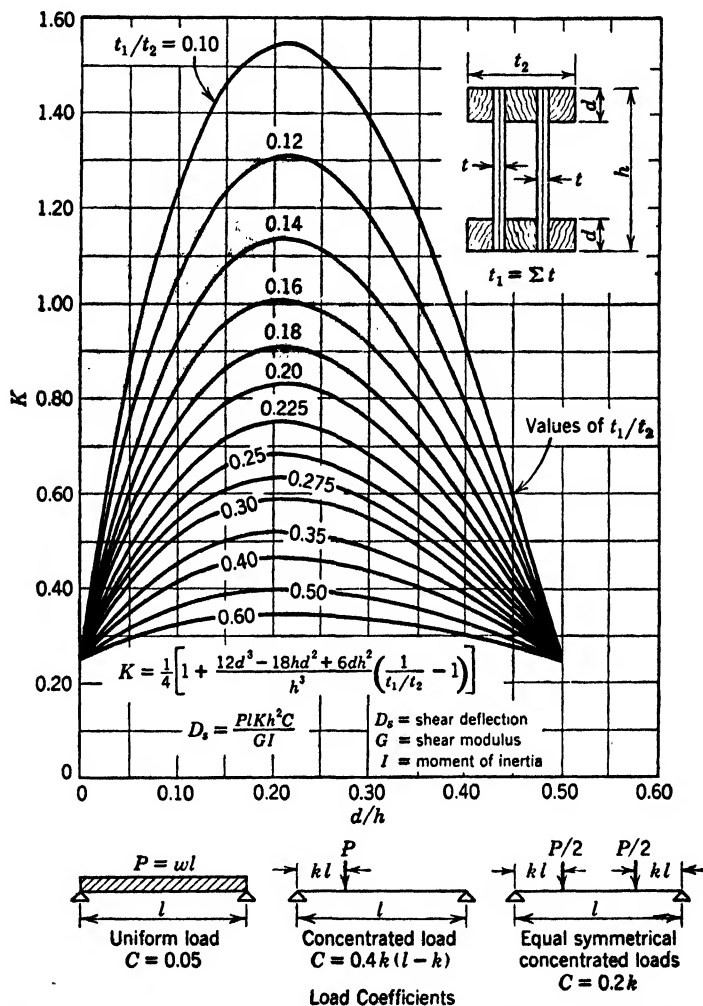


FIG. 4-20. Section Constant for Shear Deflection. Sections symmetrical about horizontal and vertical axes.

formulas. The "true modulus" is simply a value 10 per cent higher than the modulus of elasticity commonly listed for the given species, inasmuch as the ordinary moduli for wood contain an allowance of 10 per cent to provide for shearing deflection in a solid rectangular beam



having a span-depth ratio of about 14. This approximate shear correction is not required when the accurate correction previously described is made.

It should be noted that, if a beam is glued, the lumber should be initially dry, and the elastic moduli will accordingly be higher than for green lumber of the same species.

### 5. Lateral Stability

Plywood beams are ordinarily relatively deep by comparison with their over-all width, so that attention must be given to their lateral

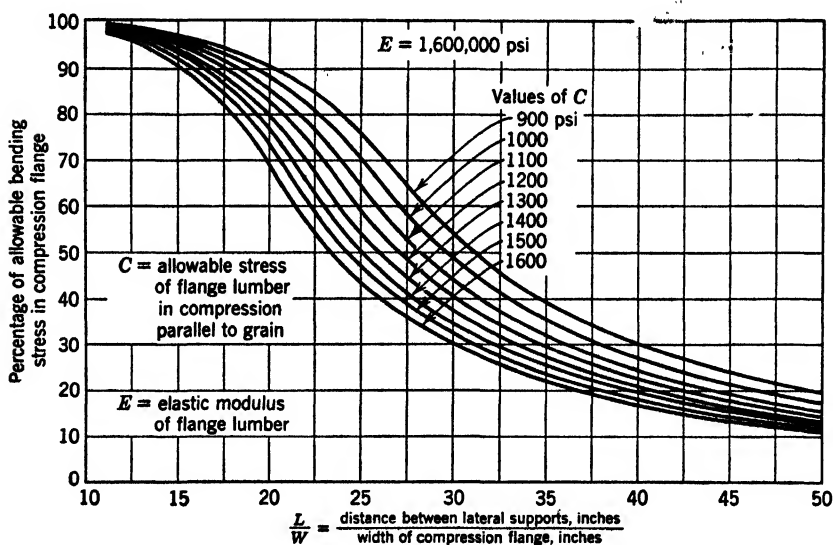


FIG. 4-21. Effectiveness of Lateral Bracing of Plywood-Beam Compression Flanges.

stability. It is desirable to provide lateral support systematically and to have some method of gaging its effectiveness. The upper flange may be considered as a column that tends to deflect sidewise between points of support. Then the bending stress in the compression flange will depend on the ratio of the distance between supports to the flange width, in the same way that the allowable stress in a wood column is varied with its  $l/d$  ratio, to avert buckling.

The wood column formulas themselves may be used to obtain the percentage of allowable bending stress permissible in the compression flange (see Fig. 4-21).

There are formulas expressing critical buckling loads of various sections, including solid rectangular beams and I beams, under a number of conditions of restraint and loading.<sup>6,7</sup>

## 6. Stiffeners

Plywood beams usually require several vertical stiffeners glued to the webs between inner surfaces of the top and bottom flanges. The function of these stiffeners is to stabilize the web against shear and buckling, to separate the flanges under loading, to distribute loads into the beam at the point of application, and to space the flanges accurately during the fabrication process.

From a design standpoint they may be divided into two classes—those which distribute concentrated loads and those which stabilize the web. One stiffener, of course, may serve both purposes. Thus, the minimum stiffener dimension parallel to the span will be

$$x = \frac{P}{wc_{\perp}} \quad (4-9)$$

where  $x$  = stiffener thickness, in.

$P$  = concentrated load or reaction, lb

$w$  = total beam width, in.

$c_{\perp}$  = allowable bearing strength of the flange lumber perpendicular to the grain, psi

This formula will be conservative, providing the load is evenly distributed across the full beam width, because there will be some longitudinal stress distribution along the beam.

Complete design information on the size of intermediate or web-stabilizing stiffeners is not available. In general, their cross-sectional areas should provide adequate column strength to resist any compressive forces from the flanges and to provide sufficient bearing area. They should also give enough glue area against the web to prevent the latter from buckling. A suggested minimum is  $\frac{3}{4}$  in.

To reduce the possibility of buckling in the stiffener it is recommended that the thickness be at least one sixth of the outstanding dimension if only one edge of the stiffener is glued to the web.<sup>7</sup> With this requirement, for example, a  $\frac{3}{4}$ -in. stiffener would be adequate for a beam having a flange width of  $4\frac{1}{2}$  in. or less.

## 7. Web Buckling

The maximum clear distance required between intermediate stiffeners to maintain the full shear strength of the web depends on the plywood

thickness, the clear distance between top and bottom flanges, the angle between the face grain of the plywood and the beam's axis, the elastic constants, moisture content, and the thickness of the veneers composing the plywood. For practical design purposes, however, only the first two factors need be considered.

Figure 4-22 shows maximum values of the stiffener spacing  $b$  which will prevent buckling and develop the full web shearing strength of

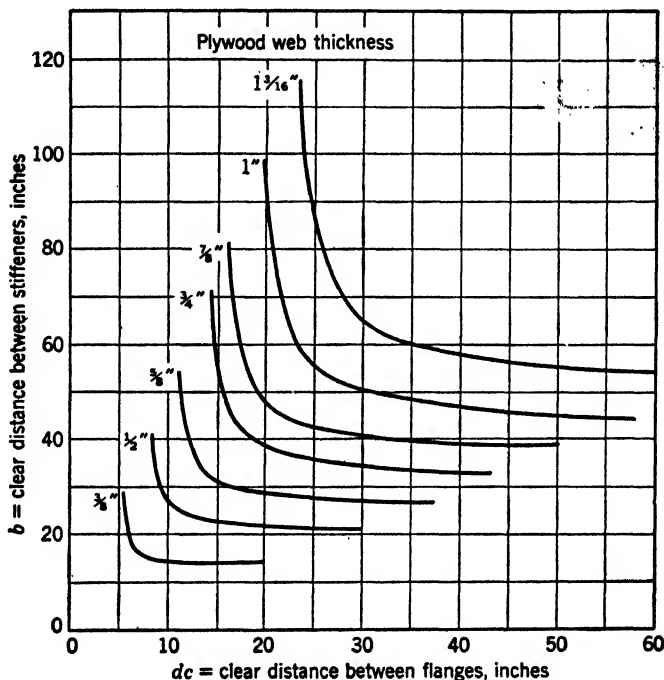


FIG. 4-22. Basic Intermediate Stiffener Spacing for Plywood Beams.

various thicknesses of plywood and for various distances between the flanges  $d_c$ . It was derived from data published in reference 8. The curves were computed for Douglas fir plywood at 15 per cent moisture content having its face grain parallel to the span; values read from it will be slightly conservative if the face grain is perpendicular to the span. The plywood constructions listed are those shown on page 222.

The allowable clear distance between intermediate stiffeners increases rapidly as the actual shear stress in the web decreases below the allowable. To determine the spacing for reduced shear stresses, let the basic spacing for 100 per cent shear stress, read as the ordinate in Fig. 4-22

be called  $b$ . Then, as the actual web shear stress varies from 100 to 50 per cent of the allowable value, the stiffener spacing may be varied uniformly from  $b$  to  $3b$ . This relationship may be expressed by the formula,

$$b' = b \left( 1 + \frac{100 - p}{25} \right) \quad (4-10)$$

where  $b'$  is the allowable stiffener spacing which corresponds with the percentage  $p$  of the allowable shear stress that actually exists within the section. A value of  $p$  less than 50 per cent should not be used. The clear distance between stiffeners for spacing the flanges accurately during fabrication should probably not exceed  $3b$ .

### 8. Joints and Splices

Where lumber or plywood of full beam length is not available, joints become necessary. The most desirable method of splicing longitudinally, both in plywood and lumber, is with a glued scarf joint. A slope often used for softwood lumber is 1 in 12; this value will develop most of the clear wood strength and usually the full strength of a piece of structural lumber or plywood containing the normal growth characteristics.

Scarf joints in lumber are usually made by the fabricator when the beam is built but in plywood are best made at one of the plywood mills equipped for such an operation.

End butt joints may be used in a flange that is laminated from a number of pieces. An end butt joint however should not be considered as transmitting any tensile stress, because it is impossible to glue an end grain joint satisfactorily, or any compressive stress, because the joint may be left slightly open in fabrication. Furthermore, butt joints tend to cause points of stress concentration within the flange. Accordingly, butt joints should be systematically staggered along the beam—a minimum distance of 24 in. between butt joints in the same flange is suggested for  $\frac{3}{4}$ -in. lumber. Also desirable is a maximum amount of staggering of butt joints with respect to the width of the beam.

Although several mills are now producing scarfed Douglas fir plywood panels up to 50 ft long, stock lengths will be utilized for many built-up beams and girders. For these, web butt-joints with plywood splice plates glued over both sides are usual. The splice plates should be full beam depth where possible. Although some of the flexural stress in the web is transferred into the flange, numerous tests have not shown any failure resulting from the increased flange stress.

The face grain of the splice plates should be parallel with the span, particularly if this is also the face-grain direction of the web itself. When this is the case, the stress on the secondary glue line between the contacting faces of the web and the splice plate is shear parallel to the grain, a property in which wood is considerably stronger than in rolling shear. However, a rolling shear stress still exists within the splice plate between the face and the next inner ply, so that this is the limiting design stress. Furthermore plywood usually has a larger percentage of the total thickness parallel to the face grain than perpendicular to it, and in this case the parallel-grained veneers are the ones that carry the stress.

The total thickness of the parallel plies in both splice plates should equal or exceed the total thickness of the parallel plies in the web. Also the total thickness of each splice plate should not be less than half the web thickness.

A satisfactory formula for computing the lengths of plywood splice plates which will develop the full bending and shear strength of the web is

$$l = \frac{\sqrt{(Fft||)^2 + (vt)^2}}{S_R} \quad (4-11)$$

where  $l$  = total length of splice plate measured perpendicular to the joint, in., when splice plates are glued to both faces of the web

$F$  = the form factor of the beam (not adjusted by a factor of  $10/9$ )

$f$  = allowable fiber stress in bending of the flange lumber, psi

$t||$  = the sum of the thicknesses of those plies in the web whose grain is parallel to the span, in.

$v$  = allowable horizontal shear stress in the web, psi

$t$  = the thickness of the web being spliced, in.

$S_R$  = allowable rolling shear stress for plywood, psi (not reduced for stress concentration, as in the case of the flange-web joint)

This formula is derived by assuming that the maximum unit stress transmitted across the web joint is equal to the resultant of the maximum fiber stress carried by the parallel plies in the web and of the maximum shear stress carried by the full thickness of the web. Half this stress is taken into the splice plate on each side of the web by shear in the glue joint, although the flange itself also acts as a splice plate.

One approximation of this formula is that the allowable rolling shear stress is not reduced for stress concentration, although some probably

exists. This discrepancy with theory appears justified by numerous test results which show that the values given by this formula are conservative.

As previously mentioned, the formula is designed to cover both bending and shear simultaneously. Although maximum bending and shear seldom occur at the same section, it is recommended that all splices be sufficient to develop the full web strength so as to insure that the beam will act as a continuous member. A minimum value of 6 in. is suggested for the splice plate length.

TABLE 4-9. SPLICE PLATE LENGTHS, IN.

$$l = \frac{\sqrt{(F \eta \parallel)^2 + (v)^2} *}{S_R}$$

Face grain of webs  
parallel to span  
 $v = 210$  psi  
 $S_R = 79$  psi

Plywood Thickness, in.	Fiber Stress, psi						
	1200	1400	1600	1800	2000	2200	2400
$\frac{3}{8}$ —R	6.0	6.0	6.0	6.0	6.0	6.0	6.0
$\frac{3}{8}$ —S	6.0	6.0	6.0	6.0	6.0	6.0	6.0
$\frac{1}{2}$	6.0	6.0	6.0	6.0	6.3	6.8	7.5
$\frac{5}{8}$	6.0	6.0	6.4	7.1	7.8	8.6	9.4
$\frac{3}{4}$	6.0	6.0	6.4	7.2	7.9	8.6	9.4
$\frac{7}{8}$	6.6	7.5	8.5	9.5	10.5	11.4	12.4
1—R	8.0	9.3	10.6	11.8	13.0	14.3	15.5
1—S	6.0	6.8	7.7	8.6	9.4	10.2	11.2
$1\frac{1}{16}$	8.3	9.5	10.8	12.0	13.2	14.4	15.7

\* A minimum value of  $l = 6$  in. has been used.

Table 4-9 gives splice plate lengths found from equation 4-11 for the commonly used plywood thicknesses and lumber stresses. A horizontal shear stress of 210 psi and a rolling shear stress of 79 psi have been assumed, these values corresponding to the So-2-S grade of plywood commonly used for structural purposes. A form factor of 0.80 has been taken as adequately close, yet conservative. It has also been assumed that the face grain of the plywood webs is parallel to the span.

The spliced section may then be checked to determine the additional stress thrown into the flange from the web. As strain-gage measurements have shown the splice plates to carry stress, a suggested method of analysis is to consider the splice plates, rather than the web, when checking the moment of inertia. (The form factor, however, will remain the same.) A more conservative procedure would be to omit consideration of both splice plates and jointed web in calculating the moment of inertia.

## SUMMARY OF DESIGN METHOD

The following outline summarizes the design method. It is assumed that the bending moments and shears have been computed, and that a trial member has been selected for checking. Then the following points should be considered.

1. The maximum bending stress is computed from the formula,

$$f = \frac{Mc}{FI} \quad (4-12)$$

where  $F$  is computed with the gross dimensions of the section and  $I$  with the net.

2. The maximum horizontal shear stress is computed from the formula,

$$v = \frac{VQ}{It} \quad (4-13)$$

where  $Q$  and  $I$  are computed from the gross dimensions.

3. The maximum flange-web shear stress is found by the formula

$$s = \frac{VQf l(t_1)}{Id(\Sigma t)} \quad (4-14)$$

4. The actual deflection may be checked against the allowable by applying appropriate deflection formulas, taking shear into account.

5. Lateral support should be provided at points depending on the compression flange width and stress.

6. Bearing and intermediate stiffeners should be provided and spaced so as to develop the full shear strength of the web.

7. Any butt joints occurring in flange members should be properly spaced. Splice plates of appropriate size should be provided for web butt joints.

*Example.*—It is required to design a girder to support a uniformly distributed permanent load of 1000 lb per foot on a 48-ft span. The girder will not be exposed to the weather.

Lumber used in the compression flange will be Dense Select Structural Douglas fir, and in the tension flange Select Structural Douglas fir. Dry unsurfaced lumber is available. Plywood will be unsanded Sound-2-Sides Douglas fir, Exterior-type.

Allowable plywood stresses in this example are for grades in use prior to 1947 and differ from current ones in Table 4-10.

**1. Determine Bending Moments and Shears.** Assume weight of beam at 60 lb per foot; then shear and moment diagrams will be as shown in Fig. 4-23.

TABLE 4-10

Stress	Lumber		Plywood So-2-S
	Select Structural Par. 214 WCBLG & I	Dense Select Structural Par. 214a WCBLG & I	
Extreme fiber in bending	1,600	1,800	2,188
Compression parallel		1,300	1,460
Compression perpendicular (bearing)	345	380	405
Shear perpendicular to plane of plies			210
Shear in plane of plies			26 *
Modulus of elasticity	1,600,000	1,600,000	1,600,000
Modulus of rigidity			117,000

\* For the design of splice plates an allowable rolling shear stress of 52½ psi will be used.

**2. Depth of Trial Section.** Use flexure and deflection formulas simultaneously to solve for depth, using approximations suggested on page 242. Let allowable deflection equal  $L/360$ .

$$\begin{array}{ll}
 \text{Flexure} & \text{Reflection} \\
 M = \frac{WL}{8} = \frac{FfI}{c} & d = \frac{(1.25)5WL^3}{384EI} = \frac{L}{360}
 \end{array}$$

Solving for  $WL$  gives

$$WL = \frac{8FfI}{h/2} \qquad WL = \frac{384EIL}{1.25(360)5(L^2)}$$

Equating and solving for  $L/h$ , we have

$$\begin{aligned}
 L/h &= \frac{384(1.6 \times 10^6)}{36,000(0.8)(1800)} = 11.85 \\
 \therefore h &= \frac{48 \times 12}{11.85} = 48.5 \text{ in.}
 \end{aligned}$$

A trial depth of 48 in., corresponding to a stock plywood width, will be used.

**3. Web Thickness of Trial Section, from Equation 4-1.**

$$t = \frac{1.25V}{hv} = \frac{1.25(25,440)}{48(210)} = 3.16 \text{ in.}$$



Select two webs at 1 in. plus one at  $1\frac{3}{16}$  in., giving  $t = 3\frac{3}{16}$  in.; the center  $1\frac{3}{16}$ -in. web may be dropped off where shear conditions permit, giving a section with two webs at mid-span.

**4. Trial Flange Dimensions of Center Section.** (a) Bending requirements, from equations 4-2 and 4-12:

$$I = \frac{Mc}{Ff} = \frac{3,660,000(24)}{(0.8)(1800)} = 61,000 \text{ in.}^4$$

(b) Deflection requirements (assuming constant  $I$ ) uniform load-deflection formula, increased by 25 per cent:

$$\begin{aligned} I &= \frac{(1.25)(360)5Wl^2}{384E} \\ &= \frac{(1.25)(5)(360)(50,880)(48 \times 12)^2}{384(1.6 \times 10^6)} = 61,800 \text{ in.}^4 \end{aligned}$$

$$I_{\text{webs}} = \frac{2(0.625)(48^3)}{12} = 11,500 \text{ in.}^4$$

(Table 4-5 shows that unsanded 1-in. plywood has  $\frac{5}{8}$  in. of its thickness parallel to the grain of its face plies.)

$$I_{fl} = 61,800 - 11,500 = 50,300 \text{ in.}^4$$

Let the flange consist of two pieces each of horizontally laminated 2 by 4s, surfaced to  $1\frac{5}{8}$  in. by  $3\frac{5}{8}$  in., and separated by a  $1\frac{3}{16}$  in. lumber fill. (An alternate construction would use a  $1\frac{3}{16}$  in. plywood fill, which would tend to stabilize the flange against checking.) As shown in Fig. 4-23 the flange width is then  $8\frac{7}{16}$  in., and the distance required between inner flange faces is given by the formula for the moment of inertia.

$$h_l^3 = 48^3 - \frac{12I}{w}$$

$$h_l = \sqrt[3]{48^3 - \frac{12(50,300)}{8.44}} = 33.9 \text{ in.}$$

$$\therefore d = \frac{48 - 33.9}{2} = 7.05 \text{ in.}$$

Use 5 laminations @  $1\frac{5}{8}$  in. =  $8\frac{1}{8}$  in.

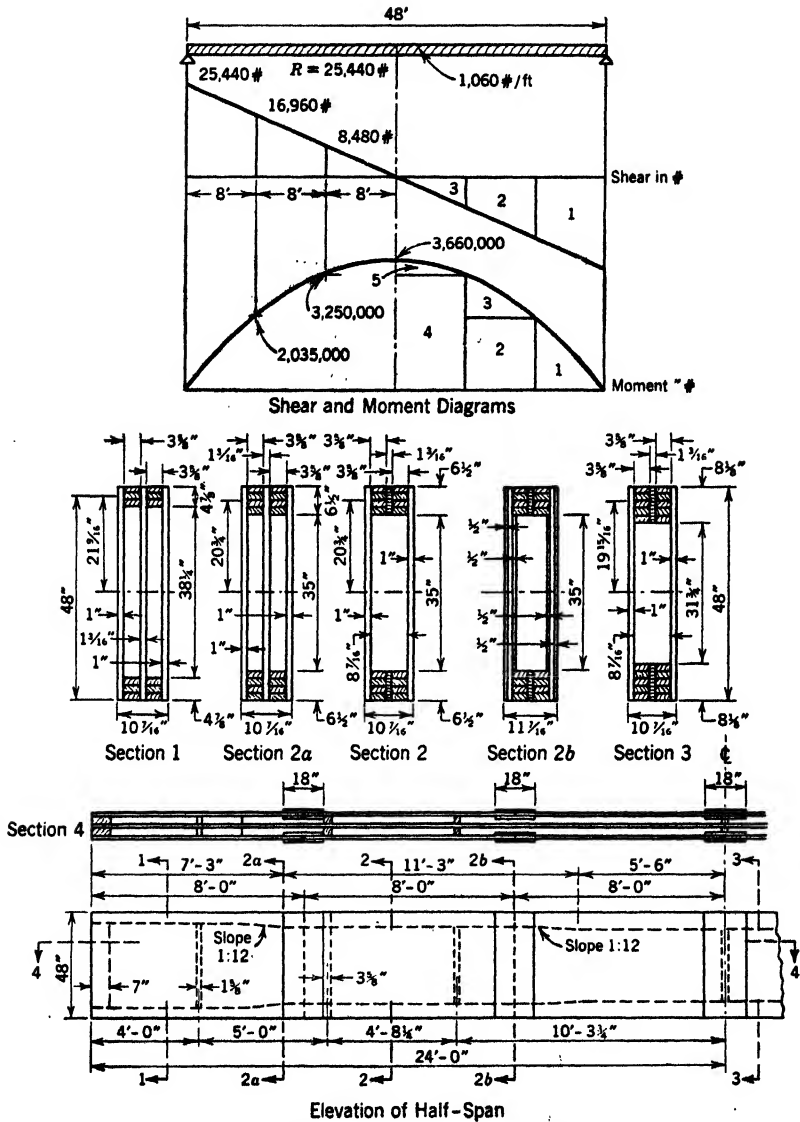


FIG. 4-23. Example of Plywood-Beam Design.

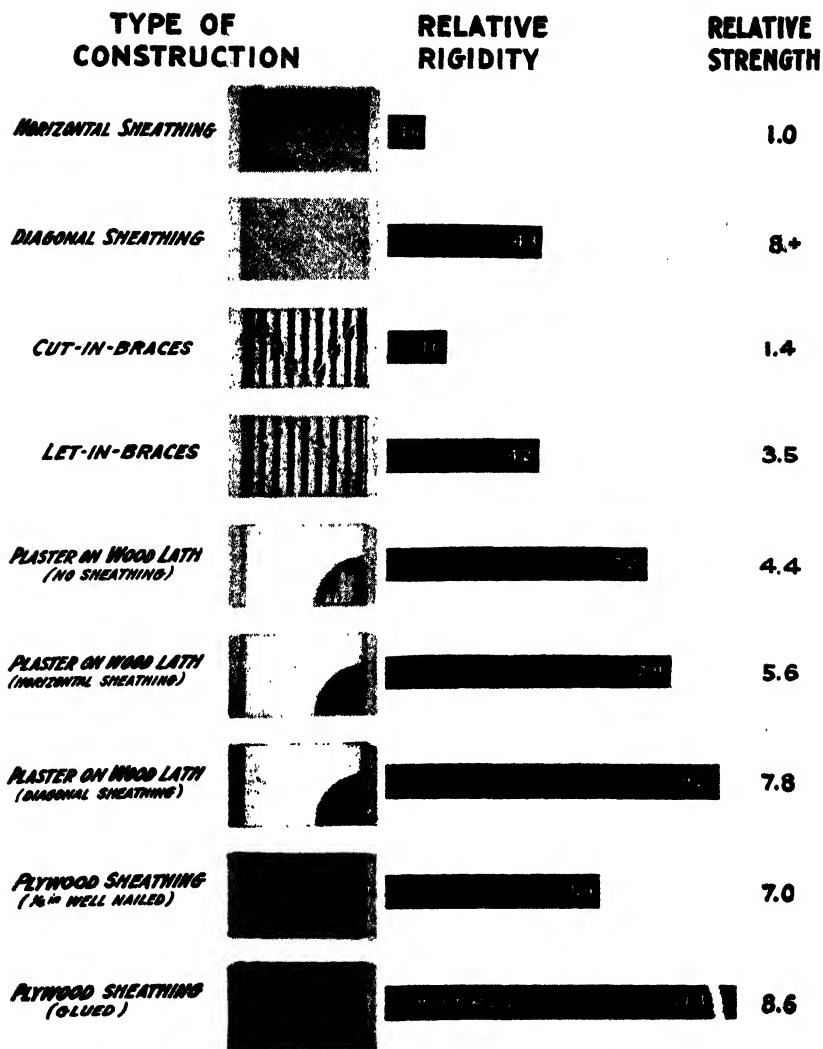


FIG. 4-24. Tests at U. S. Forest Products Laboratory, Madison, Wis.

**5. Flexure Check (Section 3, Fig. 4-23).**

$$I = \frac{2(0.625)(48^3)}{12} + \frac{8\frac{7}{8}[48^3 - (31\frac{3}{4})^3]}{12}$$

$$= 11,500 + 55,400 = 66,900 \text{ in.}^4$$

$$\left. \begin{aligned} \frac{d}{h} &= \frac{8\frac{1}{8}}{48} = 0.169 \\ \frac{t_1}{t_2} &= \frac{2}{10\frac{7}{8}} = 0.192 \\ F &= 0.723(\frac{19}{9}) = 0.804 \end{aligned} \right\} \text{(See Fig. 4-18.)}$$

The factor of  $\frac{19}{9}$  applies to the working stresses, but is considered with the form factor for convenience.

$$\text{Allowable resisting moment} = \frac{FfI}{c} = \frac{(0.804)(1800)(66,900)}{24}$$

$$= 4,030,000 \text{ in.-lb}$$

(It may be noted that the tension flange stress will be within the allowable wherever the compression flange stress is, because  $F = 0.723 < \frac{1800}{1900} = 0.89$ .)

**6. Horizontal Shear Check (Section 3, Fig. 4-23).**

$$Q = 2(0.625)(24)(12) + 8\frac{7}{8}(8\frac{1}{8})(19\frac{1}{8})$$

$$= 360 + 1365 = 1725 \text{ in.}^3$$

$$V = \frac{vIt}{Q} = \frac{210(66,900)(2)}{1725} = 16,280 \text{ lb} \quad (4-15)$$

**7. Flange-Web Shear Check (Section 3, Fig. 4-23).**

$$V = \frac{sId(\Sigma t)}{Qfl(t_1)} = \frac{26\frac{1}{4}(66,900)(8\frac{1}{8})(2)}{1365(1)} = 20,900 \text{ lb} \quad (4-16)$$

$\therefore$  Allowable shear on center section is 16,280 lb governed by horizontal shear at the neutral axis.

**8. Other Sections through Beam.** The innermost flange laminations may be dropped off, as stress conditions permit, from the center toward

the reactions. Sections shown in Fig. 4-23 have been checked by the methods shown for Section 3 to determine resisting moments and shear.

*Section 2.*

$$I = 59,100 \text{ in.}^4$$

$$d/h = 0.135$$

$$t_1/t_2 = 0.192$$

$$F = \frac{0.706}{0.9} = 0.785$$

$$\text{Resisting moment} = 3,480,000 \text{ in.-lb}$$

$$\text{Allowable horizontal shear} = \underline{16,600 \text{ lb}}$$

$$\text{Allowable flange-web shear} = 17,800 \text{ lb}$$

*Section 2a.*

$$I_{\text{net}} = 52,500$$

$$d/h = 0.135$$

$$t_1/t_2 = 0.192$$

$$F = \frac{0.706}{0.9} = 0.785$$

$$\text{Resisting moment} = 3,090,000 \text{ in.-lb}$$

The net moment of inertia of Section 2a is computed ignoring the center web because of the butt joint.

*Section 1.*

$$I = 50,350 \text{ in.}^4$$

$$d/h = 0.1015$$

$$t_1/t_2 = 0.305$$

$$F = \frac{0.735}{0.9} = 0.817$$

$$\text{Resisting moment} = 3,080,000 \text{ in.-lb}$$

$$\text{Allowable horizontal shear} = \underline{25,900 \text{ lb}}$$

$$\text{Allowable flange-web shear} = 27,000 \text{ lb}$$

The transition from Section 3 to Section 2 may be made where the bending moment is 3,480,000 in.-lb, equal to the resisting moment of

**Section 2.** This point is found to be  $18\frac{1}{2}$  ft from the reaction. The transition will be made gradually by scarfing the excess lamination at a slope of 1 to 12.

The change from two to three webs may be made at a point where the shear is 16,600 lb, the allowable horizontal shear on Section 2. This point is found from the shear diagram to be 8.35 ft from the reaction; because of the presence of secondary stresses at the point of discontinuity, the change will be made 9.0 ft from the reaction, requiring the use of either a 9-ft plywood panel or a splice.



**Fig. 4-25.** Walls and Partitions of This Prefabricated House Are Stressed-Skin Panels Consisting of  $\frac{3}{8}$ -in. Plywood Glued to 1-in.-by-3-in. Framing, with Blanket Insulation in Exterior Walls. The roof is constructed of 32-in.-by-16-ft plywood panels glued to lumber frames. The finish roof consists of shingles nailed to the plywood.

The computation of a trial section, not shown here, indicates that the flange-web shear resistance requires that the transition from four to three flange laminations be made at a point where there are three webs for contact, rather than only two. The transition to Section 1 will be made at a point just behind the splice.

**9. Check Deflection.** Because the beam sections vary along its length, the section properties used in the deflection formulas should be an average weighted with respect to the area of the shear diagram and the moment about the reaction of the area of the moment diagrams. In this case it should be sufficiently accurate to consider the half-span to consist of three parts of constant dimensions, each 8 ft long.

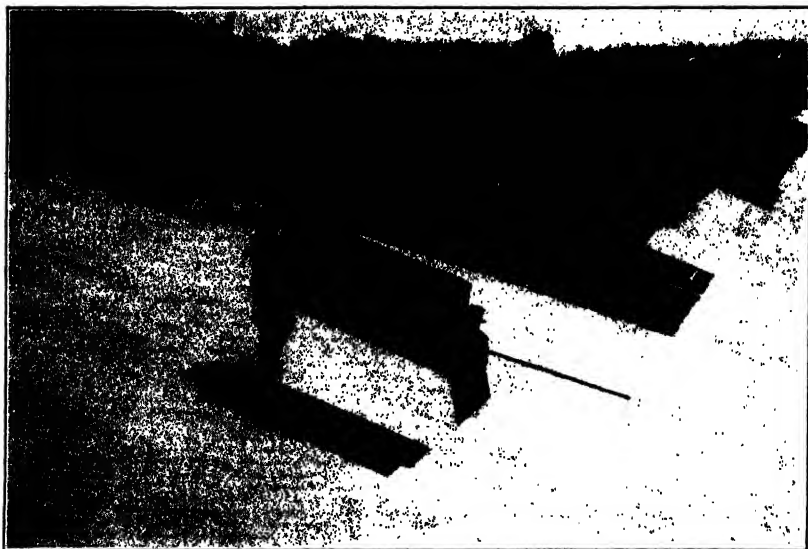


FIG. 4-26. Panels of  $\frac{5}{8}$ -in. Plywood 4 ft by 8 ft Are Rapidly Laid to Sheath This Sawtooth Roof. When well nailed across the joists, the larger panels may be relied on to provide bracing in the plane of the roof, as well as a tight deck for built-up roofing.

(a) *Bending Deflection.* For use in the deflection formula an average  $I$  for a symmetrical beam symmetrically loaded may be found from the formula,

$$I_{\text{avg}} = \frac{Ax}{\frac{Ax}{I}}$$

where  $A$  = the area of a section of the moment diagram

$x$  = the distance from the near reaction to the center of gravity of the area under consideration

$I$  = the moment of inertia of that portion of the beam corresponding to the area under consideration

Calculations (not shown here) disclose that the moment diagram  $A$  and  $x$  have relative values as shown in Table 4-11.

$$I_{\text{avg}} = \frac{112,460}{1.786} = 63,000 \text{ in.}^4$$

$$d_b = \frac{5(50,880)(48 \times 12)^3}{384(1.10 \times 1,600,000)(63,000)} = 1.140 \text{ in.}$$

(See item 4, page 247.)

TABLE 4-11

Part	$A$	$x$	$I$	$Ax$	$\frac{Ax}{I}$
1	1.356	5	50,350	6,780	0.135
2	2.085	12	59,100	24,420	0.414
3	0.810	13	59,100	10,530	0.178
4	3.250	20	66,900	65,000	0.973
5	0.273	21	66,900	5,730	0.086
				112,460	1.786

(b) *Shear Deflection.* Calculations using the shear diagram and Fig. 4-20 may be made (Table 4-12).

TABLE 4-12

Section	$A$	$d/h$	$t_1/t_2$	$K$	$AK$	$I$	$AI$
1	2.120	0.1015	0.305	0.50	1.060	50,350	106,700
2	1.272	0.135	0.192	0.79	0.992	59,100	75,300
3	0.424	0.169	0.192	0.84	0.356	66,900	28,300
	3.816				2.408		210,300

$$K = \frac{2.408}{3.816} = 0.63$$

$$I = \frac{210,300}{3.816} = 55,200 \text{ in.}^4$$

$$d_s = \frac{PIKh^2C}{GI} = \frac{(50,880)(48 \times 12)(0.63)(48)^2(0.05)}{(117,000)(55,200)} = 0.329 \text{ in.} \quad (4-17)$$

$$\text{Total deflection} = 1.140 + 0.329 = 1.47 \text{ in.}$$

$$\text{Allowable} = \frac{48 \times 12}{360} = 1.60 \text{ in.}$$



**10. Design Splices.** All end joints in the flanges, except the junction of the center fill with the web at the sixth-points, will be scarfed at a slope of 1 in 12 and glued. The joints in the 1-in. plywood webs will be butted and covered both sides with  $\frac{1}{2}$ -in. plywood splice plates. The length of the splice plates is computed from equation 4-11.

$$l = \frac{\sqrt{(Fft||)^2 + (vt)^2}}{S_R} = \frac{\sqrt{(0.74)(1800)(0.625)^2 + (210)(1)^2}}{52.5} = 16.3 \text{ in.}$$

The added stress thrown into the flange around the web splice will be computed by considering the moment of inertia of the splice plates as replacing that of the web.



FIG. 4-27. Plywood Arches Form the Ribs of This Experimental Dairy Barn. Cap strips are of lumber laminated to shape. (Courtesy Marine-Air Research Corporation, Annapolis, Md.)

It is assumed that 8-ft-long panels will be used (except for the center web, which will be a 9-ft panel) thus requiring splices at the sixth-, third-, and center points of the span. Comparison of the resisting moments with the bending moments shows the most critical splice section occurs at the third-point, in Section 2b.

$$I_{\text{ext}} = \frac{2(0.3)}{12} (48^3 + 35^3) = 7670 \text{ in.}^4$$

$$I_{\text{fl}} = \frac{8\frac{7}{8}}{12} (48^3 - 35^3) = 47,600 \text{ in.}^4$$

$$I = 7670 + 47,600 = 55,270 \text{ in.}^4$$

$$\text{Resisting moment} = \frac{55,270}{59,100} (3,480,000) = 3,250,000 \text{ in.-lb}$$

(See values for Section 2, Fig. 4-23.)

$$\text{Bending moment} = 3,250,000 \text{ in.-lb}$$

**11. Stiffener Design.** (a) *Bearing Stiffeners.* The required thickness of stiffeners at the reactions is

$$x = \frac{V}{wc} = \frac{25,400}{(10\frac{7}{8})(345)} = 7.06 \text{ in.} \quad (4-18)$$

Then the bearing stiffeners will be cut from two 4 × 8's. No other bearing stiffeners are required.

(b) *Intermediate Stiffeners.* Intermediate stiffeners will be made 1½ in. thick and of a width equal to that of the flange. However, at the point of discontinuity of the center web—that is, 9 ft from the reaction—3½-in.-by-3½-in. stiffeners will be used to help distribute the secondary stresses.

Stiffener spacings will be those for 1-in. plywood, the minimum used in this example. Figure 4-22 shows that for a clear distance between flanges of 38¼ in. (see Section 1, Fig. 4-23) the basic stiffener spacing  $b = 48$  in. Since the maximum actual shear stress at the reaction is practically 100 per cent of the allowable, the maximum spacing of 48 in. will be used. Then, as the thickness of the end bearing stiffener is 7½ in. and of the intermediate stiffener 1½ in., the first intermediate stiffener could be centered 48 in. plus 7½ in. plus 1¾ in., or 56⅝ in. from the end.

Reference to the shear diagram shows that at this point the external shear will be 20,500 lb, or 79 per cent of the resisting horizontal shear strength of the section. Then the allowable clear distance between the first and second stiffeners will be

$$b' = 48 \left( 1 + \frac{100 - 79}{25} \right) = 88.4 \text{ in.} \quad (4-19)$$

The second intermediate stiffener will be located where the center web ends, 9 ft from the reaction, and the first stiffener will be located 48 in. from the reaction.

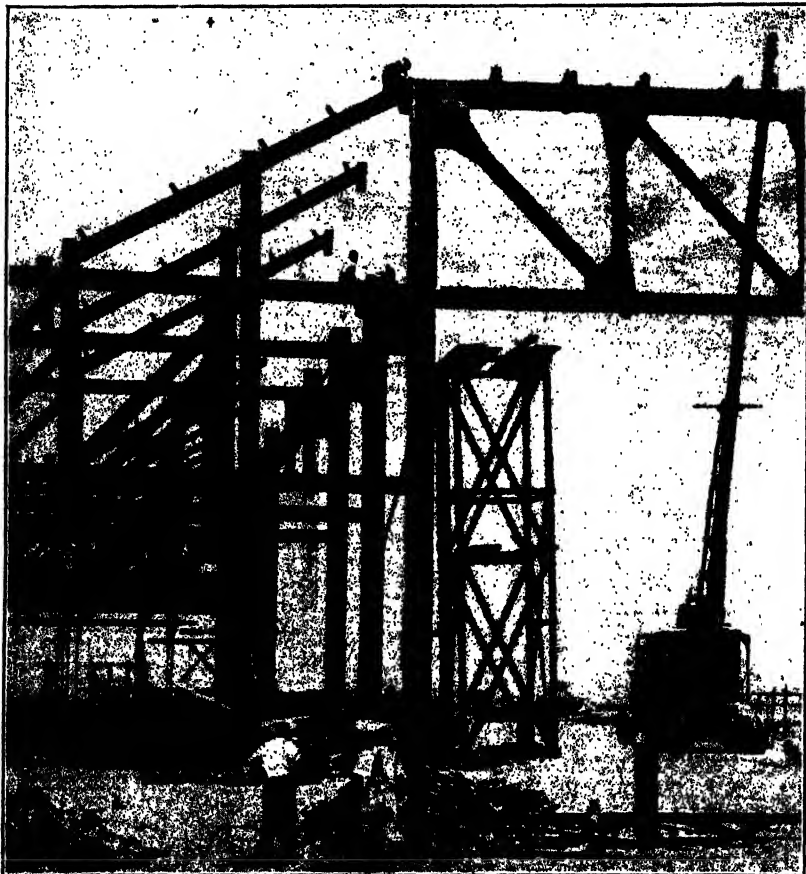


FIG. 4-28. Plywood Gusset Plates  $2\frac{5}{8}$  in. Thick and Timber Connectors Simplify the Joint Details on These Wood Trusses. Spans varied from 50 to 150 ft.

The external shear at the second stiffener is found to be 15,900 lb, which is 96 per cent of the allowable on the section. The basic spacing for a flange distance of 35 in. is  $48\frac{1}{2}$  in., and the maximum allowable clear distance between the second and third stiffener is

$$b' = 48\frac{1}{2} \left( 1 + \frac{100 - 96}{25} \right) = 56\frac{1}{4} \text{ in.}$$

The external shear at the third stiffener is 10,800 lb, or 65 per cent of the allowable, and the permissible spacing between the third and fourth stiffener is

$$b' = 48\frac{1}{2} \left( 1 + \frac{100 - 65}{25} \right) = 116\frac{1}{2} \text{ in.}$$

It will be sufficient to place the fourth stiffener at the center line, a distance of 10 ft  $15\frac{1}{16}$  in. from the third stiffener.



FIG. 4-29. The Sides of This Conveyor Were Formed of Plywood Girders 4 ft Deep, with Webs  $\frac{3}{4}$  in. Thick. Merchandise was transferred from one warehouse to another across the street through the conveyor on gravity rollers.

**12. Lateral Stability Check.** Because the load is uniformly distributed, presumably the top flange is supported laterally at frequent intervals. However, if this were not the case, the spacing of supports would depend on the percentage of allowable stress in the compression flange.

In part 3, the percentage of allowable stress is

$$\frac{3,660,000}{4,030,000} = 91\%$$

In parts 2 and 1, these percentages are found to be 95 and 48 respectively.

As the modulus of elasticity of the flange lumber is 1,600,000 psi, Fig. 4-21 may be used with a value of  $C = 1300$  psi, the allowable compression stress. For 91, 96 and 48 per cent stresses, there are found

respectively  $l/w$  values of 16.3, 13.5 and 26.4. The full beam width of  $10\frac{7}{16}$  in. may be taken for  $w$ , so that corresponding distances between lateral supports are 14.2 ft, 11.8 ft, and 23.0 ft. One arrangement of lateral supports that will meet these requirements could be achieved by placing them at the ends, quarter-points, and mid-span.

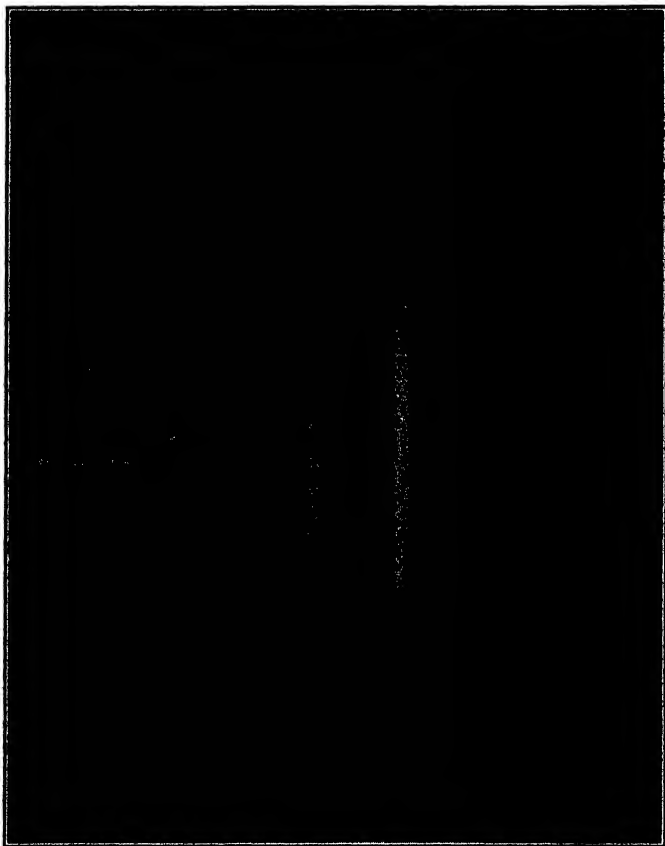


FIG. 4-30. The Shearing Strength and Stiffness of Plywood Are Utilized to Add Rigidity to the Railroad Boxcar, Here Being Lined with  $\frac{5}{16}$  in. Plywood Inside and Out, Nailed and Bolted to the Framing. Ceilings are  $\frac{5}{16}$  in. thick.

A check on the actual dimensions of the girder shows the weight to be 58.5 plf, sufficiently close to the original estimate.

#### ILLUSTRATIONS

In this chapter are illustrated several typical applications of plywood in housing, heavy construction, marine uses, and miscellaneous other

purposes. Figure 4-24 gives a comparison of the strength and rigidity of ordinary stud walls when constructed in various ways. The rigidity of glued plywood sheathing is seen to be especially marked. An application of "stressed-skin" construction to housing is shown in Fig. 4-25. Gussets, railroad cars, roofing, and girders are shown in Figs. 4-26 to 4-30.

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## Composite Laminated-Wood-Concrete Construction

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Composite laminated-wood-concrete construction for bridge and pier decks and miscellaneous heavy-duty services was introduced, and the original work of developing a design procedure for the structural assembly was done about 1932 by J. F. Seiler, formerly bridge engineer of the Wyoming State Highway Department and subsequently principal engineer of the Service Bureau, American Wood-Preservers' Association. Although the idea of placing concrete floors on timber joists had been conceived earlier, and many structures employing it had been constructed, no precedent for dealing analytically with the shear connection or evaluating its effectiveness in the assembly, existed. McCullough conducted tests (1932) and established design values for spikes, pipe, and metal plates employed as shear connections between timber joists (stems) and concrete slab but advocated design of the assembly as consisting of two elements acting independently rather than as a composite T beam.

The more positive functioning of the shear developer in the laminated-timber-concrete assembly and the successful results ensuing from its use in numerous structures over many years of service have amply justified the present established practice of composite design in which the elements of construction act together as a single unit.

### WHAT THE CONSTRUCTION IS

The composite timber-concrete construction, in whatever form it may be employed, functions and is the same in all structural respects as the commonly called "reinforced concrete." The reinforcement is the wood, and it lies outside, not inside of the concrete. Like the steel bars in concrete, the wood takes the tensile stress when the construction is employed as a beam under transverse loads. When the stresses are reversed, the wood may function in compression, and steel bars em-

bedded in the concrete resist the tension. Thus, the purpose of composite construction is fulfilled, namely, to capitalize on the most advantageous properties of each element of the assembly.

The bond between wood and concrete is developed by mechanical means, not by adhesion between their contact surfaces. Plates, spikes, or dowels, firmly set in the wood member with their protruding portions subsequently embedded in the concrete, serve efficiently as shear connections. In order to maintain an intimate tight contact between concrete and wood, heavy spikes or dowels driven in the wood with heads embedded in the concrete are used. Their respective penetrations in wood and concrete should be as ample as conditions permit.

Although spikes or dowels protruding from the upper face of the wood subbase into the concrete are designed to maintain a permanent tight contact between the elements on a horizontal plane, it is obvious that no gravity forces are involved which would tend to cause a separation. The precaution is taken to provide against forces due to other causes such as temperature changes which might conceivably cause a curling action in a wide slab.

In the subject case, laminated wood strips in tight contact side by side form the "reinforcement" for the composite assembly. The laminas may be of two different depths, placed alternately so as to form rectangular grooves along one or both edges of the assembly, or the pieces may be of the same depth, placed in a staggered position so as to form similar grooves on both edges or sides of the assembly. Another method is to use pieces of different thicknesses, either the same or different depths placed alternately so as to produce similar rectangular grooves parallel with the axis of the laminas. Figures 5-1A, B, C, and D illustrate the laminated assembly.

The wood laminas are selected with respect to thickness and depth, to provide grooves of appropriate size for maximum effectiveness and economy of the shear connections. Figure 5-1E illustrates the type of connection which has been found best adapted to the laminated construction.<sup>1</sup> It is a steel plate of truncated triangular shape commonly known as a "shear developer." Under stress it acts as a partially restrained beam on three sides, of span equal to the width of the rectangular groove; hence, its thickness is vitally dependent on that dimension. Moreover, for practical reasons of preparing the "slots" into which the shear developers are placed, the least thickness compatible with proper functioning is desirable. It has been found that square grooves of sides not more than 2 in. are preferable, and in such grooves shear developers of structural-steel grade,  $\frac{3}{8}$  in. thick, or of



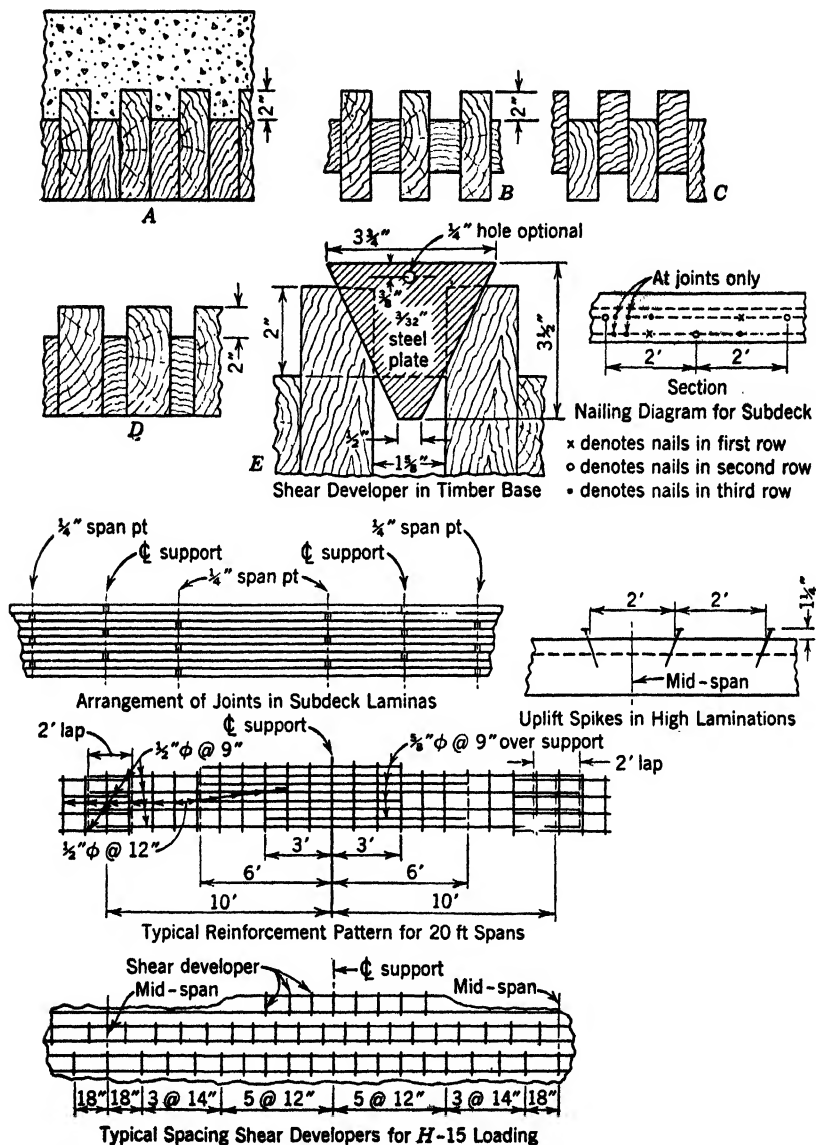


FIG. 5-1. General Arrangement and Elements of Timber-Concrete Decks.

## Purposes for Which the Construction Is Adapted 275

approximately 12 gage, will provide ample resistance to shear at reasonable spacing.

### PURPOSES FOR WHICH THE CONSTRUCTION IS ADAPTED

The laminated composite construction may be employed in numerous forms of structural members. Since for practical reasons the wood laminas are limited in depth, the construction is best adapted for shallow beams, or slabs of indefinite width. It is applicable to trestle construction spanning from pier to pier or to trusses where the slabs will extend from floor beam to floor beam without stringers or other supporting media. The construction usually falls into the category of slabs with reinforcement parallel to direction of traffic, and the lateral distribution of concentrated loads is calculated accordingly.

Special conditions may, of course, suggest the use of the composite laminated-wood-concrete assembly in numerous novel forms. The discussion to follow deals with the application of the arrangement to slab construction.

Used in this manner, the laminated-wood portion of the composite slab becomes the base on which the concrete mat is subsequently poured with or without extraneous supporting members or centering, depending on the relation of dead weight of the construction to span length, thickness of base, and conditions of restraint at supports. Frequently, it is found economical and convenient to employ the wood base as a self-supporting member. In that case no other means are required to sustain all the dead load of the construction between floor beams or piers. Obviously, then, the dead-load stresses must be segregated and considered in connection with the wood base only.

Under certain conditions, it may prove advantageous to reduce the thickness of the wood base relative to the over-all thickness of slab and depend on centering to support the dead weight until the concrete sets and the slab can function as a composite member to carry both the dead and the live loads. In the "self-supporting" type, the thickness of the wood section may vary from one half for light sections to two thirds of the total thickness of composite slab for heavy sections. In the other, which may be described as the non-self-supporting type, the ratio remains rather constant at about one third or slightly more.

The slab construction is best adapted to pier and bridge decks subject to vehicular or other heavy-duty traffic. It also may be employed to advantage for heavy-duty floors in mills, warehouses, or other structures where relatively long spans must be used. The concrete surface provides an effective smooth hard surface well adapted to the require-

ments of traffic. At the same time it serves as an excellent medium for lateral distribution of concentrated loads. By virtue of the shear connections, it acts in bending as part of the composite slab when subjected to load.

### DESIGNING THE STRUCTURE

In what follows we attempt to analyze the construction, determine the several beam properties, and thereby provide a basis for the calculation of stresses when the slab is under load. Properties are determined by transforming the composite section in the following manner: When the net concrete thickness is less than half the over-all depth of beam, it is assumed that the modulus of elasticity of wood equals that of concrete, or  $E_c = E_w$ . When the net concrete thickness is one-half or more the over-all depth of beam, the modulus of elasticity of concrete is assumed as twice that of wood, or  $E_c/E_w = 2$ . It has been found through experience that greater refinements in the design are not justified because the several assumptions on which the procedure is based must, of necessity, be approximate rather than precise. In general, it is found that for slabs where the concrete is relatively thin compared to the total depth, stresses resulting from the two assumptions of the value of  $E_c/E_w$  show relatively unimportant differences.

### DEAD-LOAD MOMENTS IN THE LAMINATED SUBDECK

#### INTERIOR SPANS

Positive and negative dead-load moments in the interior spans of a continuous multispan structure will differ from those in the end spans or those of a symmetrical two-span structure. In the interior spans, considered as fixed at the ends, a theoretical distribution of the moments for a beam of uniform section uniformly loaded would give for the negative moment  $66\frac{2}{3}$  per cent of the simple-span moment. However, because of the loss of stiffness occurring when stresses exceed the elastic limit of the wood, there is a redistribution of moments tending to relieve this condition, prior to failure.<sup>2</sup>

Where the negative moments are large compared to the positive, in a series of continuous spans it is usually considered preferable to determine the stresses and proportion the composite deck on the basis of its performance under ultimate rather than design loads. It follows, then, that a redistribution of moments applicable to the case in hand is in order. Thus, from Fig. 5-2, for a calculated negative moment of  $66\frac{2}{3}$

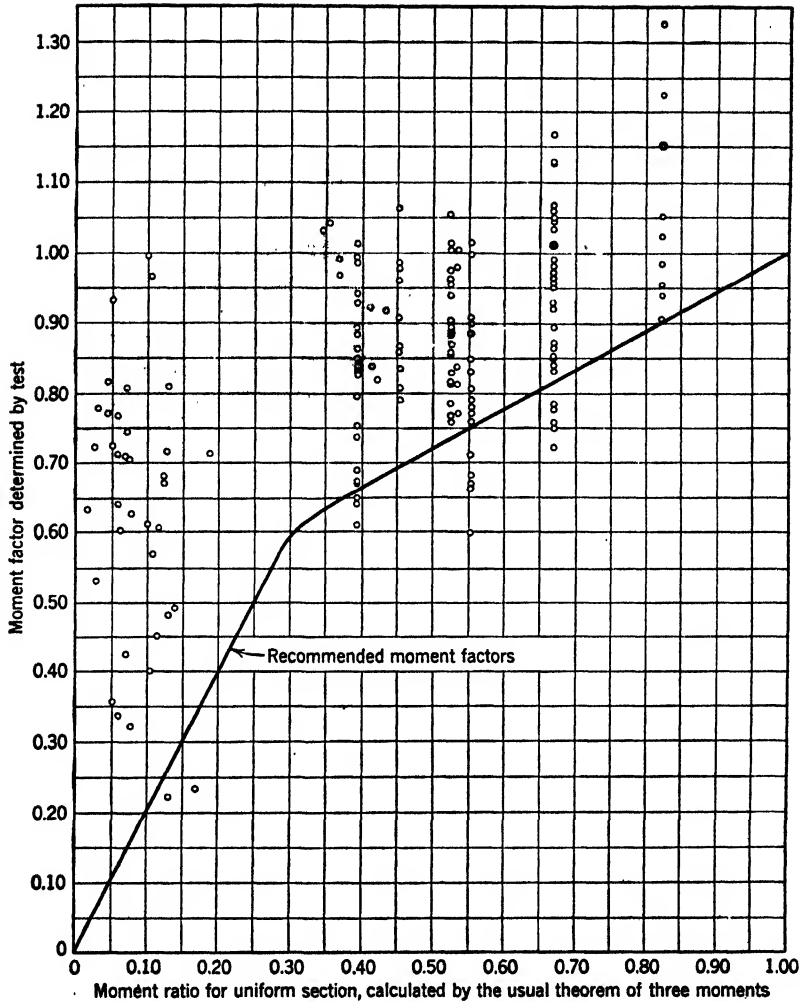


Fig. 5-2. Chart Showing the Relation between the Calculated Ratio of Moments and the True Ratio to Be Used When Calculating the Ultimate Strength of Continuous Beams. Horizontal scale represents the ratio of positive to negative moment determined by any of the usual formulas. The vertical scale represents the ratio determined by test. (Courtesy U. S. Forest Products Laboratory)

per cent of the simple-span moment—that is, for a ratio of positive to negative moment of 0.50—we find that the actual moment will be 72 per cent of the negative moment. This is 58 per cent of the simple-span moment.

Where there is a reduction in the support section due to joints in the laminas, a further redistribution of moments occurs. As a result, the point of inflection moves toward the support, still further reducing the negative moment. Practical experience has shown that this may be taken as 50 per cent of the simple-span moment, reflecting a total decrease of 25 per cent in negative moment, but compensated for by a 50 per cent increase in positive moment. As a practical matter, this redistribution of moments affords a more favorable basis for design since it tends to place the emphasis on simple-span performance and to that extent avoids the hazards associated with continuous-beam or slab construction.

#### END SPANS OR TWO-SPAN STRUCTURE

Usually the negative moment will be greater in this case than for the interior spans of a multispan structure. For a beam of uniform section, uniformly loaded, fixed at one end and free at the other, the calculated negative moment will be equal to the simple-span moment. As before, this will be reduced to about 83 per cent of the simple-span moment. For the usual pattern of composite subdecks the negative moment for design purposes may be taken as close to 71 per cent of the simple-span moment. This redistribution adds approximately 20 per cent to the positive moment near mid-span while relieving the maximum negative stress by about 30 per cent. For end spans of a multispan structure, the negative moment will have an intermediate value which can be taken as 60 per cent of the simple-span moment. In order to equalize these stresses with those of interior spans, it is generally advisable to decrease the length of end spans accordingly. For a symmetrical two-span structure the length should be reduced or the section increased, whichever may be the more appropriate or economical arrangement.

Maximum design moments in per cent of simple-span moment in subdeck are given in Table 5-1.

#### DEAD-LOAD MOMENTS IN COMPOSITE SLAB

When the non-self-supporting type of composite deck is used, or when the wood base is supported by centering during construction, the

dead load, including the weight of the wood and the concrete, will be borne by the composite section. Stresses due to dead and live loads need not necessarily be segregated, but for uniformity of arrangement

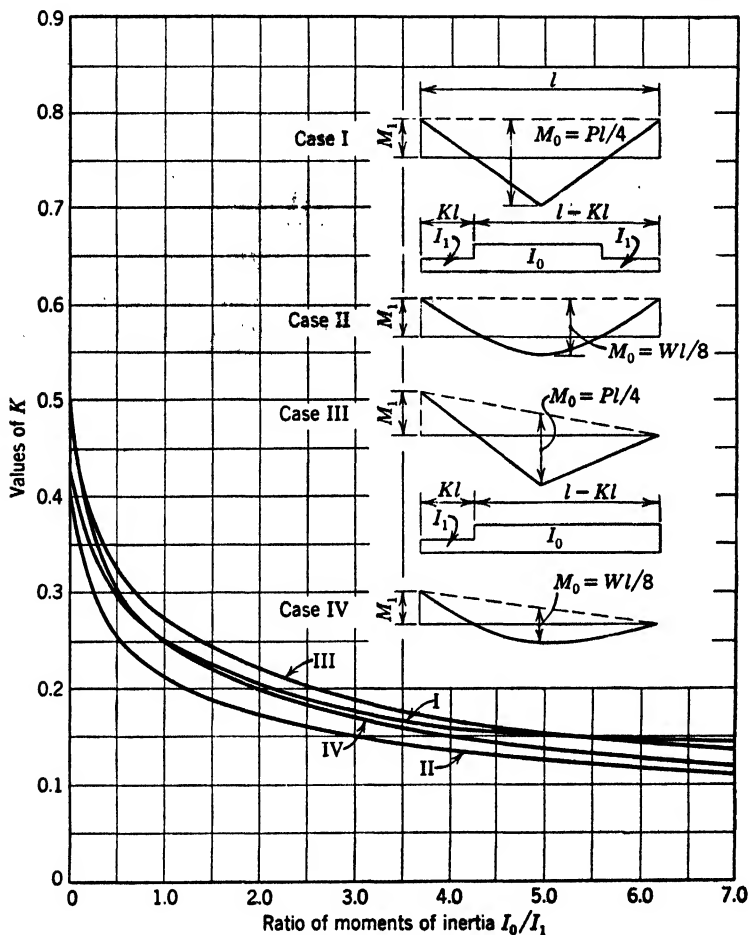


FIG. 5-3. Ratio of Moments of Inertia  $I_0/I_1$  versus  $K$  for Various Bending Conditions. (Univ. Illinois Eng. Expt. Sta. Bull. Ser. 343, p. 55, 1943.)

Table 5-1 giving dead-load moments in terms of the simple-span moment is provided. Usually it will be found convenient to use these values, superimposing them on those given for live loads, rather than making entirely new computations for the combined loadings.

It may be seen, of course, that the dead load is uniformly distributed over every span of the structure, and the moments are computed ac-

cordingly. To accomplish this it is necessary to determine the relation between moments of inertia of the positive (mid-span) and negative (support) sections, and also the location of the point of inflection, or node point. The fraction of span length  $k$  from support to node point depends on conditions of loading and restraint at supports, as well as moments-of-inertia ratios and may be determined from equations rationally or empirically derived.

Figure 5-3<sup>1</sup> is a graph of these equations for the fundamental conditions of span loading and end restraint indicated in cases I to IV, inclusive. It may be assumed that cases I and II represent, approximately, conditions pertaining to the interior spans of a multispan structure, whereas cases III and IV pertain to spans of a continuous beam or slab of two equal spans, which are referred to in the following as "symmetrical two-span." The  $k$  values for end spans of a multispan structure may be considered lying between those for the two aforementioned conditions.

Since the moment of inertia ratios are very nearly the same as in the self-supporting type, the values of  $k$  (Fig. 5-3),<sup>1</sup> the fixed-end moments and carry-over factors for end and interior spans of the self-supporting type will be identical with those of the non-self-supporting type.

#### LIVE-LOAD MOMENTS IN COMPOSITE SLAB

Having determined the values of  $k$  pertaining to the several cases of span loading and end restraint, we may now proceed to the calculation of the live-load moments with due regard to the  $M/I$  areas, fixed-end moments, and carry-over factors applicable to the case in hand.

If any beam, whether homogeneous or composite, contains in its upper or lower edges a material which responds differently to compressive and tensile stress, and if such beam be restrained at one or both ends, it will have under load two different moment-of-inertia values. One will apply to the portion of beam under positive and the other to that under negative moment. For composite slabs of the type and general dimensions considered here, the positive and negative moments of inertia are taken as 0.083 and 0.037 ft<sup>4</sup>, respectively, giving a ratio of approximately 2.25, which conforms rather closely to that of the commonly used sections.

For purposes of illustration, the Standard Highway Loadings<sup>2</sup> of the American Association of State Highway Officials will be used in determining the live-load moments. For wheel loading the standard

H-15 truck will be used. Its weights, dimensions, clearances, and load distribution between front and rear axle are shown in Fig. 5-4. As wheel loadings invariably produce maximum moments in short spans, the standard lane loadings<sup>3</sup> are not considered. However, maximum moments in terms of simple-span moment have been computed for uniform as well as concentrated loadings placed in accordance with AASHO specifications in a multiple-span structure, and from these the

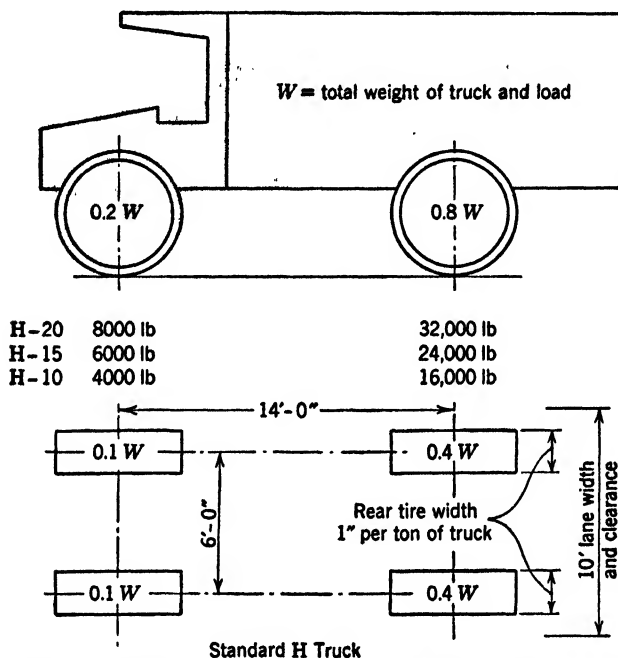


Fig. 5-4. Standard Highway Truck Loadings. (AASHO, *Standard Specifications for Highway Bridges*, 1941.)

numerical values can be obtained for any standard AASHO lane loading.

(a) **Concentrated (or Wheel) Loading.** Maximum calculated moments for the several span conditions are as shown in Table 5-1. It may be noted that the negative moments are relatively low because, according to highway specifications, truck loads cannot be placed in adjacent spans if the spans are less than 40 ft in length. Generally speaking, composite spans of this type do not exceed 30 ft in length.

(b) **Uniform Loading.** The maximum positive and negative moments shown in Table 5-1 are computed by loading only those spans



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in any structure which contribute to the moment at the point in question. This conforms to current highway specifications, which permit the use of discontinuous loadings.

TABLE 5-1. MAXIMUM BENDING MOMENTS—PER CENT OF SIMPLE-SPAN MOMENT

Span	Maximum Uniform Dead-Load Moments				Maximum Live-Load Moments			
	Wood Subdeck		Composite Slab		Concentrated Load		Uniform Load	
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
Interior	50	50	55	45	75	25	75	55
End	70	60	70	60	85	30	85	65
2-Span *	65	70	60	75	85	30	80	75

\* Continuous beam of 2 equal spans.

### CALCULATING THE STRESSES IN THE COMPOSITE CONSTRUCTION

In the "self-supporting" type of construction the dead and live loads will be considered separately. Since the dead load will be carried entirely by the laminated-wood base the stresses will be computed with due regard to its applicable dimensions and beam elements and will be applied accordingly. Live loads will be borne by the composite section, and these stresses will be computed from the appropriate composite beam dimensions and elements.

Dead-load shearing stresses will be neglected, as is customary in wood-beam design where the width is equal to or greater than the depth. Laminated-wood slabs obviously fall into this classification where shear is not a factor. Accordingly, shear due to live load only will be computed and assumed to be resisted entirely by the shear developers. In the self-supporting type of composite slab all dead load is borne by the subdeck; consequently, there is no composite action and therefore no shear to be transmitted from one element to the other, and the shear developers will not function under dead load. Obviously there will be no dead-load stress in the concrete.

For the non-self-supporting type where centering is required, both dead and live loads will be carried by the composite section, and the stresses will be computed accordingly. In this case both dead- and live-load horizontal shear will be resisted by the shear developers, and the concrete will be subjected to dead as well as live-load stress.

The composite section will be treated as a homogeneous beam of wood of the same dimensions for all cases in which the net concrete thickness is less than half the over-all beam depth. For all cases where the net concrete thickness is half or more the over-all beam depth, the composite beam will be transformed to a hypothetical wood section, but in computing the beam properties concrete below the neutral axis is disregarded. In other cases where subjected to negative moments, the concrete also will be neglected, and the transformation will be made by considering steel and wood areas only, with due regard to their position in the assembly and their respective moduli of elasticity.

Where concentrated live loads are involved, it will be necessary first to determine the lateral distribution of such loads on the finished construction. This is a problem of the most complicated nature, made even more difficult by the combination of elements making up the full slab. For this reason, recourse is had to field and laboratory tests on composite slabs of different widths. The most comprehensive of these tests<sup>9</sup> was that made by the Maryland State Roads Commission in 1939.

For the usual case of two passing trucks with the adjacent wheels 3 ft apart, the Maryland tests give approximately 5 ft for the lateral distribution of a single wheel under the influence of the adjacent wheels of the passing trucks. A test made at the Bureau of Standards<sup>5</sup> on a slab 5 ft in width gave a distribution of 80 per cent of the slab width, or 4 ft, for a load at mid-span on that particular slab. It is reasonable to assume that the distribution would have been increased, though not proportionately, for slabs of a greater width. As a general rule, the 5-ft distribution of concentrated loads has been usually accepted in design specifications of engineers who have prepared plans of composite laminated construction.

The composite construction with its concrete surface is highly effective in increasing the lateral distribution of concentrated loads. Where the plain laminated floor is involved, it is clear that lateral distribution is obtained solely by means of the fastenings between the laminas. These are subjected to shear on the vertical planes between adjacent members. Loads are thus transmitted from one lamina to another by the fastenings which function in bearing, crosswise of the grain of the wood. Therefore, unless the fastenings are very numerous, the lateral transfer of load is strictly limited. If the fastenings are too numerous, the integrity of the slab is likely to be reduced by splitting of the wood.

In the composite slab, shear on the vertical planes parallel to the wood laminas is carried very largely by the concrete itself, aided by the

transverse reinforcement. Meanwhile, the fastenings in the laminas, being very considerably below the neutral axis of the slab (considered now as a beam in a transverse direction), act as tensile reinforcement rather than in shear, thus contributing materially to stiffness of the slab in a transverse direction on which the lateral distribution of load depends. In this case, the holding power of spikes or of dowels, whichever may be used for the fastenings, is an important factor in the ability of the slab to transmit load laterally.

The lateral distribution of concentrated loads on the composite slab will be affected, owing to the position of the load in the span. The maximum distribution of 5 ft for a concentrated load under the influence of adjacent loads pertains to a mid-span position, and on the assumption of a considerable width of slab on either side. Where a wheel load approaches the roadway edge the curb section, including (or plus) the width of slab equal to the allowable clearance between wheel and curb, should be of sufficient strength to sustain it.

When the concentrated load approaches the supports, some reduction in lateral distribution will result. Very few tests have been made for loads in such position. It is generally assumed, however, that the lateral distribution for loads in the critical position for shear, for example, will not exceed 80 per cent of that when the load is at mid-span. Tests at the Bureau of Standards gave 70 per cent of the slab width for lateral distribution with the load at the quarter-point as compared to 80 per cent of the slab width with the load at mid-span. It has been a generally accepted procedure to take 4 ft for lateral distribution of concentrated loads when in position for shear as compared to 5 ft when the load is in position for maximum moment or at mid-span.

The following design assumptions and symbols are employed:

- (1)  $\frac{E_c}{E_w} = 1$  for beams in which the net concrete thickness is less than half their over-all depths.
- (2)  $\frac{E_c}{E_w} = 2$  for beams in which the net concrete thickness is half or more their over-all depths.
- (3)  $\frac{E_s}{E_w} = 18.75$  (for Douglas fir and southern pine).

where  $E_c$  is modulus of elasticity for concrete,  $E_w$  is modulus of elasticity for wood, and  $E_s$  is modulus of elasticity for steel.

## (4) Lateral distribution for concentrated load:

For moment,  $W = 5.0$  ft

For shear,  $W = 4.0$  ft

where  $W$  is equivalent width of slab over which a concentrated load is uniformly distributed.

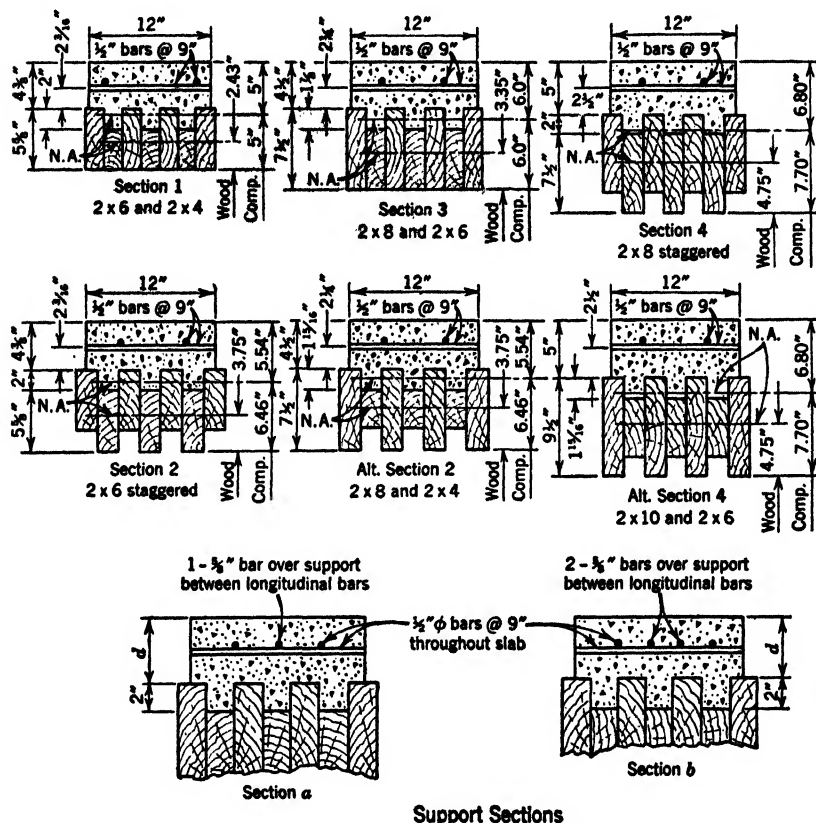


FIG. 5-5. Arrangements of Timber, Concrete, and Reinforcing Steel in Timber-Concrete Construction.

## (5) Working stresses:

- Timber: According to grades specified, namely, 1200f, 1400f, 1600f, or 1800f.
- Concrete: 1000 psi in compression.
- Steel: 18,000 psi.
- Shear developers: 1750 lb each for 3/82-in.-thick steel plate in groove 2 in. or less in width.

TABLE 5-2. PROPERTIES OF SECTIONS

Section	Moment Inertia, <i>I</i> , in. <sup>4</sup>	Resisting Moment *		Distance to Extreme Fiber †		
		Concrete	Steel	Wood	Conc.	Steel
Mid-span Section—Composite						
1	1,000	200,000		5.00	5.00	
2	1,397	252,000		6.46	5.54	
3	1,728	288,000		6.00	6.00	
4	2,541	374,000		7.70	6.80	
Support Section—Composite						
1 (a)	349		83,750	3.75		4.00
(b)	455		126,500	4.30		3.45
2 (a)	508		104,500	5.09		4.66
(b)	654		153,100	5.65		4.10
3 (a)	626		116,000	4.57		5.18
(b)	809		168,000	5.13		4.62
4 (a)	887		141,900	6.00		6.00
(b)	1,136		200,000	6.58		5.42
Mid-span Section—Wood						
1	117			2.43		
2	232			3.75		
3	313			3.35		
4	512			4.75		
Support Section—Wood						
1	78			2.43		
2	155			3.75		
3	209			3.35		
4	342			4.75		

$$E_c/E_w = n$$

$n = 1$  for all sections in which the net concrete thickness is less than half the over-all beam depth

$n = 2$  for all sections in which the net concrete thickness is half or more the over-all beam depth

$f_c = 1000$  psi     $f_s = 18,000$  psi     $f_w =$  value assigned to grade used

$$E_c/E_w = n = 18.75 \text{ for all sections}$$

\* Inch-pounds.

†  $y$  = inches

- (6) Impact: Working stresses for timber include an allowance for impact up to 100 per cent. Impact therefore will be neglected in computing the live-load stresses for timber, but an allowance of  $33\frac{1}{3}$  per cent is made for steel and concrete elements.

### Properties of Composite Beam—12-in.-Wide Section

#### 1. MID-SPAN (POSITIVE) SECTION (FIG. 5-6)

(a) *Net Concrete Thickness Less than Half Over-all Beam Depth.* The specimen shown is made up of alternate laminas of nominal dimensions 2 in. by 8 in. and 2 in. by 6 in. with  $4\frac{1}{2}$  in. of concrete, net, above

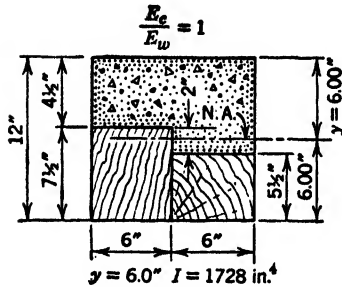


FIG. 5-6.

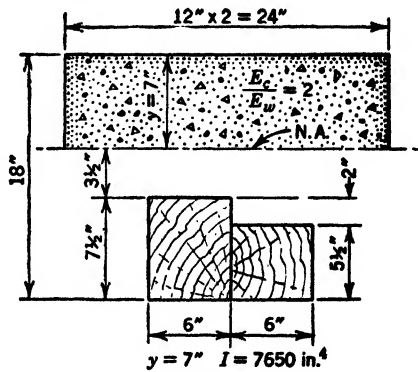


FIG. 5-7.

the high pieces. Since the surfaced dimensions will be about  $\frac{1}{2}$  in. less (in depth) and need not be considered laterally, the section may be considered as shown for a 12-in.-wide beam.

Table 5-2 shows beam properties for sections with over-all depth twice or more the net thickness of the concrete. Figure 5-5 shows sections, properties of which are given in Table 5-2.

(b) *Net Concrete Thickness Half or More Over-all Beam Depth* (Fig. 5-7). Taking moments about top of concrete gives

$$24y \cdot \frac{y}{2} = 12y^2, \text{ statical-moment transformed concrete section}$$

$$\left. \begin{array}{l} 45 \times 14.25 = 641.2 \\ 33 \times 15.25 = 503.3 \end{array} \right\} \text{statical-moment wood section}$$

$$(78 + 24y)y = 1144.5 + 12y^2$$

$$12y^2 + 78y - 1144.5 = 0$$

$$y = 6.96, \text{ say } 7 \text{ in.}$$

$$I = 7650$$

$$\begin{aligned}
 + \frac{24 \times 7^3}{3} &= 2744 \\
 + \frac{12 \times 11^3}{3} &= \frac{5324}{+8068.0} \\
 - \frac{6 \times (3\frac{1}{2})^3}{3} &= 85.74 \\
 - \frac{6 \times (5\frac{1}{2})^3}{3} &= \frac{332.74}{418.48} \quad -418.48 \\
 I &= 7649.52
 \end{aligned}$$

Table 5-3 shows properties for sections with net concrete thickness half or more the over-all beam depth.

## 2. SUPPORT (NEGATIVE SECTION)

A specimen calculation of properties for a "full" negative section is shown here simply to illustrate the method employed. The full section is required for moment-distribution purposes only. The net section

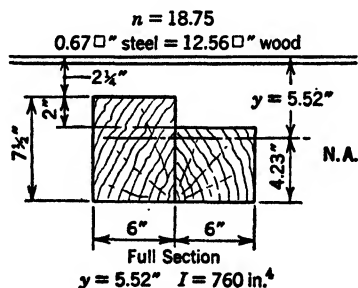


FIG. 5-8.

must be used for calculating maximum stresses over the supports. Each negative composite section will have either a "light" or "heavy" steel area, owing to stress requirements. These will be indicated as *a* and *b*, respectively, in the table. For convenience, the moment of inertia of the "full" sections may be taken as very nearly 20 per cent greater than that of the "net" sections.

(a) *Full Section (Fig. 5-8)*. Taking moments about center of steel gives

$$\left. \begin{array}{l} 45 \times 6 = 270 \\ 33 \times 7 = 231 \end{array} \right\} \begin{array}{l} \text{statical-moment} \\ \text{wood section} \end{array}$$

$$\underline{12.56 \times 0 = 0}, \quad \begin{array}{l} \text{statical-moment} \\ \text{transformed steel} \\ \text{section} \end{array}$$

$$90.56 \cdot y = 501$$

$$y = 5.52$$

$$4 \times (4.23)^3 = 302.7$$

$$\left. \begin{array}{l} 2 \times (3.27)^3 \\ 2 \times (1.27)^3 \end{array} \right\} = 74.0$$

$$\underline{12.56 \times (5.52)^2 = 382.7}$$

$$I = 759.4, \text{ say } = 760 \text{ in.}^4$$

(b) *Net Section* (Fig. 5-9). Since every third wood lamina is cut over the supports, there remains a two-thirds wood section at these points; in other words, in a 12-in.-wide composite deck section there will be but an 8-in.-wide wood section. This is equally divided between the 8-in. and 6-in. laminas.

As previously pointed out, the dead-load shear is neglected, as it will be relatively small and therefore unimportant, particularly in view of the ample wood section. The live-load shear is important because it must be carried entirely by the shear developers. In the case of the

non-self-supporting type the dead load will, naturally, be added to the live load for these calculations. The method generally employed will be to place the concentrated live load, in position for maximum shear, usually at the quarter-point of span or somewhat closer to the support. With uniform loading that portion of the load between the supports and points distant from them equal to the height of the beam is neglected.

The bending moment at the critical point, computed with the load in that position, divided by the pertinent lever arm for the section, gives the total shear on the junction plane between the load and support.

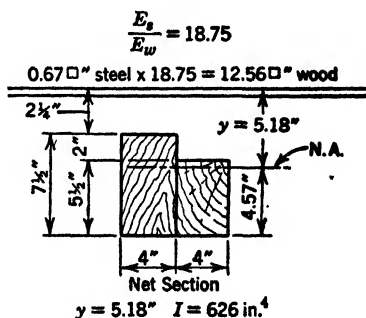


FIG. 5-9.



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This total divided by the working value of one shear developer determines the number required in this area. The spacing of the shear developers in the grooves is then calculated. This spacing is usually maintained between the support and the quarter-point on either side, and increased gradually to a limiting value from the quarter-points either way to mid-span. In general, a maximum spacing of 18 in. at mid-span is used. As a practical matter, it is believed that a minimum spacing at or near the support should be not less than 5 in.

The working value, 1750 lb for one shear developer, given in the "Design Assumptions," derives from the original conception of its bearing value parallel to the grain, on the area of embedment in the wood. The allowable working stress, in bearing parallel to grain on metal plates, was usually taken at 1750 psi \* for dense southern yellow pine or Douglas fir. It was assumed that a bearing area † of approximately 1.33 sq in. could be secured, but to allow for inaccuracies in placing, splits, and other defects, such as wane and knots, the bearing area was conservatively estimated as 1.00 sq in., against end grain, or parallel to grain. Bending of the shear developer made from structural steel and with three-point support in the usual width of groove obviously would not be critical. Test results<sup>5</sup> confirm the original assumption.

Although the so-called "uplift" spikes or dowels are effective in resisting horizontal shear, they are neglected in the design calculations. They are intended solely to maintain an intimate contact between the concrete and the wood of the composite assembly. Premises for the rational determination of their number, arrangement, and spacing are obscure, but certainly a uniform pattern of placing is indicated.

Practical experience with numerous structures in exposed locations has shown that, when these are properly driven in the raised (alternate) laminas of the timber subbase at intervals of 2 to 4 ft, no case of separation has been observed. The spikes or dowels (usually of spiral type) should have an ample penetration in the timber with their protruding heads or upper portion well imbedded in the concrete. They should be driven in vertical planes parallel to the laminas and be inclined upward toward the near support at an angle of approximately 30° with the vertical.

\* Following the 20 per cent increase in working stresses for structural timbers adopted as an emergency measure during the war, and generally recognized as standard since, a value of 2050 psi is now generally accepted.<sup>4</sup>

† Usually in excess of 2.00 sq in. for standard shape and size of shear developer presently in use.

Heavy spikes of 60d size, or  $\frac{1}{4}$ -in.-outside-diameter 7-in.-long dowels placed as previously noted will be ample to resist the curling action of the concrete due to differential temperatures of the top and bottom sides. Where extreme temperature variations are not to be encountered, it has been common practice to limit the use of this item to a crossband pattern dividing the slab into areas approximately 4 ft square, net, between the 12-in.-wide bands.

With such a pattern spikes or dowels would be driven in longitudinal and transverse rows in the following manner: Select four adjacent raised (high) laminas at the longitudinal axis of the structure, and place spikes or dowels at 2- to 4-ft intervals in each lamina. Leave a clear space of 4 ft either side of the strip just doweled, and repeat the original operation, continuing thus until the sides of the structure have been reached. The spacing of the doweled strips should be so adjusted as to permit the last strip to occur at the edges of the structure. Here the dowels should be spaced at the minimum (2-ft) distance.

The transverse strips of doweled laminas will be had by simply placing the devices in each raised or high lamina across the spaces left open between longitudinal strips or bands. Three dowels spaced at 6 in. and staggered in alternate laminas will provide suitable width of band, starting at the free ends of the structure, including expansion ends, and spaced 4 ft clear, throughout the length of the structure.

#### TEMPERATURE STRESSES

Since the two elements of the composite assembly are rigidly joined together but respond differently to temperature changes,\* stresses will be set up in each and transmitted between them through the shear developers. It is usually assumed that construction takes place at an approximately median temperature; hence, for an extreme variation of 120°F from low to high, for an exposed location it may be assumed that a range of 75°F either way from the median will be an ample allowance for stress calculations.

The following symbols are used:

\* *The Wood Handbook* of the USDA Forest Products Laboratory states, "In the case of wood the thermal expansion is so small as to be unimportant in ordinary usage. Different investigators are not in close agreement in their values of this property of wood. . . ." The coefficients given vary from 0.0000011 for yellow birch to 0.0000053 for ash, with 0.000003 for pine. It is likely that a value of approximately 0.000002 will serve as an average for commonly used structural wood. The generally accepted coefficient of concrete is 0.000006.

$A_w$  = area of wood section

$A_c$  = area of concrete section

$C_w$  = thermal coefficient of wood parallel to the grain

$C_c$  = thermal coefficient of concrete

$C_c - C_w = C$

$E_w$  = modulus of elasticity of wood

$E_c$  = modulus of elasticity of concrete

$f_w$  = unit stress in wood at point of restraint

$f_c$  = unit stress in concrete at point of restraint

$\delta_w$  = elastic deformation of wood

$\delta_c$  = elastic deformation of concrete

$t$  = temperature change in degrees Fahrenheit

Since the coefficient of wood is less than that of concrete, it is obvious that no restraint will be imposed on the movement of the wood by temperature changes. In other words, the wood will be free to expand or contract in a normal manner, resulting in a change of length, per unit, of  $C_w \cdot t$ . The concrete now having changed in length freely along with the wood and to an equal extent still has a margin of movement per unit  $(C_c - C_w) \cdot t$ , in order to respond to the temperature change. Since the wood has completed its movement, it will resist the tendency of the concrete to extend its change, and this resistance will cause a unit strain or elastic deformation in the wood of  $\delta_w$  at the plane of juncture with the concrete. Thus, the total change in length, per unit, of the wood is

$$C_w \cdot t + \delta_w$$

If the concrete were free to move, its change in length, per unit, would be  $C_c \cdot t$ . Hence, the difference, or  $C_c \cdot t - (C_w \cdot t + \delta_w)$  equals the unit strain or elastic deformation in the concrete, at its surface or plane of juncture with the wood or

$$C_c \cdot t - (C_w \cdot t + \delta_w) = \delta_c \quad (5-1)$$

Since  $\delta_w = f_w/E_w$  and  $\delta_c = f_c/E_c$ , we may write

$$C_c \cdot t - \left( C_w \cdot t + \frac{f_w}{E_w} + \frac{f_c}{E_c} \right) = 0 \quad (5-2)$$

Since the restraint to movement of the concrete flange occurs at the junction of wood and concrete, through the shear connection, its effectiveness may be expected to diminish, roughly, in proportion to distance from the junction plane. As a matter of fact, McCullough<sup>8</sup>

found that the top (exposed) surface of the concrete responded to temperature changes in a nearly normal unrestrained manner. The test results also indicated that the restraining force of the shear connection spent itself at a point one-third the depth of the timber stem above the lower extreme fiber. According to these findings and in view of the shallower depth of wood in the laminated, as compared to the beam-stem composite type,\* the stress diagram may be shown as in Fig. 5-10. Secondary bending stresses of opposite sign are induced by the moment ( $f_w \cdot A_w \cdot h/3$ ) which tend to produce this result, but

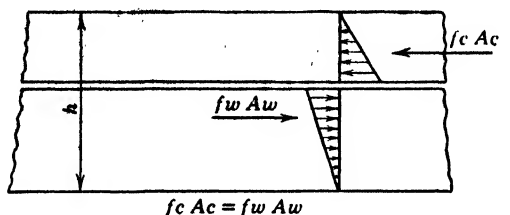


FIG. 5-10.

these are small compared to the direct stresses caused by the restraining force of the shear connection. The secondary stresses will be considered later and are neglected here. Thus, from Fig. 5-10 and for equilibrium,†

$$f_c \cdot A_c = f_w \cdot A_w \quad \text{or} \quad f_w = \frac{f_c A_c}{A_w} \quad (5-3)$$

and, substituting in equation 5-2 gives

$$C_w \cdot t + \frac{A_c f_c}{A_w E_w} + \frac{f_c}{E_c} - C_c t = 0$$

Let  $C_c - C_w =$  net coefficient  $C$ , of concrete over and above that of wood, or  $C_c = C$  when  $C_w = 0$ . Put  $E_w = \frac{1}{2}E_c$ . Then

$$f_c = \frac{C \cdot t \cdot E_c \cdot A_w}{2A_c + A_w} \quad (5-4)$$

For a temperature range of 75° F either way and a net value of  $C$  of 0.000004, using the composite section illustrated in the calculation of properties of the beam, or  $A_c = 66 \text{ in.}^2$  and  $A_w = 78$  and  $E_c = 3,000,000$ , we find, from equations 5-3 and 5-4,

\* The Oregon tests were made on T beams with concrete flange and timber stem.

† The bending stresses balance the couple shown.

$$f_w = 285 \text{ psi}$$

and

$$f_c = 335 \text{ psi}$$

From the stress diagram of Fig. 5-10 it is evident that, since the temperature stresses virtually vanish at the extreme fibers of both wood and concrete, the flexural stresses in these extreme fibers due to dead and live loads will be but remotely affected, if at all.

The horizontal shear to be transmitted by the shear developers will be, for a 12-in.-wide section,

$$\frac{335 \times 66}{2} = 11,050 \text{ lb}$$

Generally, the average number of shear developers per square foot of composite deck is very nearly 3; hence, if a length of but 1 ft of deck were involved, the thermal load falling to each shear developer would be

$$11,050 \div 3 = 3700 \text{ lb}$$

However, even in a single span of 16 ft there would be, in the half (critical) length some 24 shear developers resulting in a thermal load, per unit of

$$11,050 \div 24 = 460 \text{ lb}$$

Usually, and especially in continuous-beam spans, much greater lengths will be involved, reducing the thermal load on the individual shear developers to a negligible amount.

The thermal stresses produce bending in the slab, and this will be taken into consideration. With reference to the "specimen" section, the moment is

$$11,050 \times \frac{h}{3}$$

or

$$11,050 \times 4 = 44,200 \text{ in.-lb}$$

Since the deck will be restrained at support or pier points, we may see a rough analogy between this and the case of dead-load moments in the continuous timber subdeck or the non-self-supporting slab. Thus it seems reasonable, and has proved so in practice, to distribute this moment on a 50-50 basis between mid-span and support points. Thus the design moment becomes

$$M_t = 22,100 \text{ in.-lb}$$

The mid-span moment will be positive for a decrease and negative for an increase in temperature and must be added to the maximum moments given in the tables. As a rule, a nominal pattern of reinforcing bars will be ample to provide for the stresses in the mid-span section when temperature changes induce tension in the concrete.

#### DESIGNING THE COMPOSITE DECK

It may be assumed that the length of structure is approximately fixed, but the designer will have considerable latitude of choice as to individual span length owing to the nature of the substructure and other local conditions such as the relative cost of materials and labor or their availability.

Further latitude in fixing the span length to be employed in multi-span structures is afforded in the choice which may be made between the self-supporting and non-self-supporting type of composite deck. The quality of the material employed naturally has an important bearing on this particular problem. For example, if concrete of a 1200-lb compressive stress is used, the arrangement naturally may be somewhat different from that in which an 800-lb concrete used with the same structural grade of timber would be employed. In order to utilize the full strength of each element of the assembly, the thickness of the concrete mat or flange should be such as to fix the neutral axis most advantageously to that end. Generally, in the non-self-supporting type of composite section, no concrete below the neutral plane is considered in determining the beam elements. Thus, the thicker the concrete flange, the relatively higher position fixed for the neutral axis, and, consequently, the relatively smaller compressive stress in the concrete compared to the tensile stress in the extreme wood fiber. This is partially compensated for by the fact that impact stress is added in the case of concrete but neglected in the case of wood.

In the following example, it is required to design the deck for a highway bridge about 230 ft in length with 30-ft over-all width for each of two sites, using the H-15 highway loading. For each site the designer is confronted with two choices, namely:

(a) Span length—relatively short or long as affected by foundation conditions.

(b) Type of composite deck—self-supporting or non-self-supporting.

At one site foundation conditions will be such as to permit timber-pile bent construction at a relatively low cost, for example, \$525 per pier. At the other, the piers will have to be of a type or size which will

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increase their cost to \$1150 per pier. In each case we may compare the cost of the following layouts:

$$10 \text{ spans @ } 20 \text{ ft} = 200 \text{ ft}$$

$$2 \text{ spans @ } 16 \text{ ft} = \underline{32 \text{ ft}} \quad \text{Total } 232 \text{ ft}$$

or

$$6 \text{ spans @ } 30 \text{ ft} = 180 \text{ ft}$$

$$2 \text{ spans @ } 24 \text{ ft} = \underline{48 \text{ ft}} \quad \text{Total } 228 \text{ ft}$$

At the first site a saving of \$2100 will result from the use of 7 rather than 11 piers. If the 30-ft spans can be built not to exceed \$2100 more than the 20-ft spans, this will probably result in the more economical layout. At the other site a considerably wider margin of saving in piers is available, namely, \$4600, to absorb the higher cost of the 30-ft-span construction. Since the minimum composite section may be used for the 20 ft span, there is no point in examining shorter-span layouts.

For the 20-ft-span layout the simple-span moment for the H-15 loading \* is 144,000 in.-lb per foot width of slab. From Table 5-1 we find the maximum negative moment to be

$$\text{For interior span, } 25\% \text{ of simple-span moment} = 36,000 \text{ in.-lb}$$

$$\text{Adding } 33\% \text{ impact} = 48,000 \text{ in.-lb}$$

and the corresponding positive moments,

$$\text{For interior span, } 75\% \text{ of simple-span moment} = 108,000 \text{ in.-lb}$$

$$\text{Adding } 33\% \text{ impact} = 144,000 \text{ in.-lb}$$

Positive and negative moments are increased by 22,100 in.-lb to allow for thermal loads (for temperature variation of 75° F either way from median).

For the preliminary calculations, a self-supporting type of composite section will be considered. Since in the self-supporting section there will be no dead-load stresses in the concrete of mid-span section or steel of the support section, we may select from Table 5-2, for trial, a section having ample resisting moment with respect to concrete and to steel for the maximum calculated bending moments pertaining to their respective locations. For Section 1a,

Resisting moment, positive—200,000 in.-lb with respect to concrete.

Resisting moment, negative—83,750 in.-lb with respect to steel.

\* The H-15 loading of the American Association of State Highway Officials.

The combined live load and thermal bending moments are, for interior spans

Positive— 130,100 in.-lb

Negative— 58,100 in.-lb

Adding 33 per cent impact gives

Positive— 166,100 in.-lb

Negative— 70,100 in.-lb

It will now be necessary to compute the stress in the wood in order to determine whether the working value is exceeded. A 1600-lb f grade is to be used. Section 1a weighs 92 psf, and the simple-span dead-load moment for a 20-ft span will be 55,200 in.-lb, which when distributed will be for interior spans,

Positive— 27,600 in.-lb

Negative—27,600 in.-lb

and the dead-load stress in the wood, accordingly, will be

$$f_w = \frac{27,600 \times 2.43}{78} = 860 \text{ psi at support}$$

or

$$f_w = \frac{27,600 \times 2.43}{117} = 575 \text{ psi at mid-span}$$

If we remember that working stresses in wood include allowance for impact, the live-load stress in the wood will be

$$\frac{58,100 \times 3.75}{349} = 625 \text{ psi at support}$$

and

$$\frac{130,100 \times 5.00}{1000} = 650 \text{ psi at mid-span}$$

Total stress in wood is

$$860 + 625 = 1485 \text{ psi at support}$$

$$575 + 650 = 1225 \text{ psi at mid-span}$$

Stress in concrete is

$$\frac{M_y}{I} = \frac{166,100 \times 5.00}{1000} = 830 \text{ psi}$$



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Stress in steel is

$$\frac{M_v}{I} = \frac{70,100 \times 4.00 \times 18.75}{349} = 15,100 \text{ psi}$$

The lateral distribution of the 12,000-lb wheel load for shear will be 4 ft 0 in., giving 3000 lb per foot width of slab. Placed in critical position for shear ( $3d = 30$  in. from support), the end reaction will be 2625 lb.

The bending moment, including impact, is

$$2625 \times 30 \times 1\frac{1}{3} = 105,000 \text{ in.-lb}$$

(Total shear on neutral plane from support)

$$105,000 \div \frac{2.0}{3} = 15,750 \text{ lb}$$

$$15,750 \div 2.5 = 6300 \text{ lb shear on 1 sq ft}$$

$$6300 \div 1750 = 3.6 \text{ shear developers per square foot}$$

For 2-in. surfaced lumber the standard thickness will be  $1\frac{5}{8}$  in., thus giving 3.69 grooves per foot width of slab. Thus,

$$\frac{3.6}{3.69} = 0.975 \text{ shear developers per foot per groove}$$

$$12 \div 0.975 = 12.3\text{-in. spacing in each groove, say 12 in.}$$

This will represent the minimum spacing applicable to the region between the support and the adjacent quarter-points. In the remainder

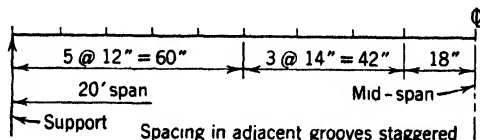


FIG. 5-11.

of the span the spacing will increase gradually from 12 in. to a maximum of 18 in., as shown in Fig. 5-11.

Alternate rows of shear developers will be staggered with respect to that shown previously. This will give 18 and 19 shear developers per groove or an average of  $18\frac{1}{2}$  throughout the span. Then

$$18\frac{1}{2} \times 3.69 \div 20 = 3.41 \text{ average number of shear developers per square foot of deck}$$

Experience has shown that a reinforcement pattern throughout the slab of  $\frac{1}{2}$ -in. round bars with longitudinal bars spaced 9 in. center to center and transverse spaced 12 in. is ample. These will constitute the nominal steel area for temperature and shrinkage stresses. A considerable amount of experience indicates such a pattern to be ample, especially where care is exercised in curing the concrete. The longitudinal bars will be 24 ft in length, centered over the supports and spliced at mid-span points.

Negative reinforcement, in addition to the regular slab bars, consists of one  $\frac{5}{8}$ -in. round bar,  $\frac{1}{4}$  of the span, or 9 ft long in this case, centered between each two longitudinal slab bars. The negative reinforcing bars are staggered to end alternately 6 ft and 3 ft from the support center. Thus part of them will extend well beyond points of inflection.

An estimate of the quantities for 1 lin ft of the structure for a 30-ft width will be then as follows:

Treated lumber:

7.36 pieces per foot width, or 221 pieces

$$= 111 \text{ pieces } 2 \times 6 = 111 \text{ FBM (feet, board measure)}$$

$$110 \text{ pieces } 2 \times 4 = 73\frac{1}{3} \text{ FBM}$$

---


$$\text{Total} = 184\frac{1}{3} \text{ FBM}$$

Shear developers:

$$30 \times 3\frac{1}{2} = 105 \text{ pieces}$$

Reinforcement:

$$24 \times 1.33 \times 0.668 \times 30 \div 20 = 32 \text{ lb}$$

$$30 \times 0.668 = 20 \text{ lb}$$

$$9 \times 1.043 \times 1.33 \times \frac{1}{1\frac{1}{2}} * \div 20 \times 30 = 17.21$$

---


$$\text{Total} = 69.21 \text{ lb}$$

Concrete:

$$\frac{5.5}{12} \times 30 = 13.8 \text{ cu ft} = 0.51 \text{ cu yd}$$

\* There will be 11 piers for 12 spans.

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Total for structure:

Treated timber:  $184 \times 232 = 42,765$  FBM

Shear developers:  $105 \times 232 = 24,400$  pieces

Reinforcing steel:  $69 \times 232 = 16,000$  lb

Concrete:  $0.51 \times 232 = 118.5$  cu yd

Since the minimum composite section of the self-supporting type is satisfactory for the 11-pier layout, there is no need of comparing the non-self-supporting type for this particular case. The comparison will be made for the 7-pier layout.

Self-supporting Section 3a weighs 110 psf.

For 30-ft interior span:

Positive dead-load moment is  $74,250$  in.-lb

Negative dead-load moment is  $74,250$  in.-lb

Positive live-load moment is  $162,000$  in.-lb

Add impact ( $\frac{1}{3}$ )  $216,000$  in.-lb

Negative live-load moment is  $54,000$  in.-lb

Add impact  $72,000$  in.-lb

Resisting moments of Section 3a:

Positive with respect to concrete— $288,000$  in.-lb

Negative with respect to steel—  $116,000$  in.-lb

Dead load stresses in wood:

$$f_w = \frac{74,250 \times 3.35}{313} = 795 \text{ psi positive}$$

$$= 795 \times \frac{313}{209} = 1190 \text{ psi negative}$$

Live-load stress (including thermal)

$$f_w = \frac{(162,000 + 22,100) \times 6.0}{1728} = 640 \text{ psi positive}$$

$$= \frac{(54,000 + 22,100) \times 4.57}{626} = 555 \text{ psi negative}$$

Total stresses in wood:

Positive—  $795 + 640 = 1435$  psi

Negative— $1190 + 555 = 1745$  psi

Stress in concrete:

$$f_c = \frac{(216,000 + 22,100) \times 6.00}{1728} = 827 \text{ psi}$$

Stress in steel

$$f_s = \frac{(72,000 + 22,100) \times 5.18 \times 18.75}{626} = 14,563 \text{ psi}$$

This section will be considered satisfactory despite the slight over-stress in the timber at the support point. If required, an 1800-lb f grade timber might be employed, although ordinarily this overstress will be

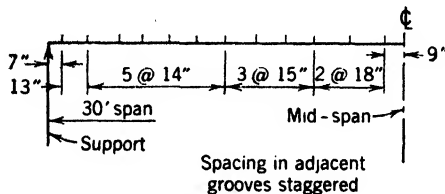


FIG. 5-12.

permitted in view of the several combinations of loadings contributing to the maximum.

Live-load shear will be calculated as before. Critical position of wheel load will be 3 ft 0 in. from support, and the reaction will be 2700 lb.

$$\text{Moment including impact} = 2700 \times 36 \times 1.33 = 129,600 \text{ in.-lb}$$

$$\text{Total shear on neutral plane} = 129,600 \div 8 = 16,200 \text{ lb}$$

$$\text{Horizontal shear on 1 sq ft} = 16,200 \div 3 = 5400 \text{ lb}$$

$$\begin{aligned} \text{Number of shear developers} \\ \text{on 1 sq ft} &= 5400 \div 1750 = 3.09 \end{aligned}$$

$$\begin{aligned} \text{Shear developers in 1 ft in} \\ \text{1 groove} &= 3.09 \div 3.69 = 0.84 \end{aligned}$$

$$\text{Minimum spacing} = 12 \div 0.84 = 14.3 \text{ in., say, 14 in.}$$

The afore-mentioned spacing (Fig. 5-12), with alternate rows staggering the positions shown, will give 24 and 25 shear developers per

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row in one 30-ft span, or an average of 24.5. In a 1-ft width of slab or a 1-ft length of bridge there will be, therefore,

$$24.5 \times 3.69 = 91 \text{ shear developers}$$

Estimate of quantities:

Treated lumber: 221 pieces in 30-ft width:

$$111 \text{ pieces } 2 \times 8 (1 \text{ ft } 0 \text{ in.}) = 148$$

$$110 \text{ pieces } 2 \times 6 (1 \text{ ft } 0 \text{ in.}) = 110$$

---

$$\text{Total} = 258 \text{ FBM}$$

Shear developers:

$$\text{Total} = 91 \text{ pieces}$$

Reinforcement:

$$34 \times 1.33 \times 0.668 \times 30 \div 30 = 30.3 \text{ lb}$$

$$30 \times 0.668 = 20.0 \text{ lb}$$

$$13.5 \times 1.043 \times 1.33 \times \frac{7}{8} \times \frac{30}{8} = 16.3 \text{ lb}$$

---

$$\text{Total} = 66.6 \text{ lb}$$

Concrete:

$$\text{Same as in Example 1} = 0.51 \text{ cu yd}$$

Totals for 228-ft structure:

$$\text{Treated timber: } 258 \times 228 = 58,800 \text{ FBM}$$

$$\text{Shear developers: } 91 \times 228 = 20,750 \text{ pieces}$$

$$\text{Reinforcement: } 66.6 \times 228 = 15,200 \text{ lb}$$

$$\text{Concrete: } 0.51 \times 228 = 116.3 \text{ cu yd}$$

In comparing the two arrangements previously estimated, for Example 1, it seems likely that the saving in piers for the 7-pier layout ( $4 \times \$525 = \$2100$ ) would be approximately offset by the additional cost of the lumber in the 30-ft spans. The selection of span length and bridge layout would, therefore, depend primarily on the relative cost and availability of materials and other local conditions.

**Non-self-supporting 30-ft Span.** In the two designs we observe the only significant difference to be in the amount of treated timber involved, namely, 16,300 bd ft. Since a savings of \$4600 in piers may be credited to the second layout, it is obvious that treated lumber in

place, would have to cost approximately \$300 per thousand board feet to equalize the two layouts. Under normal conditions such a price would be far out of line, and we may conclude, therefore, that the second plan is to be preferred. The foregoing may now be compared to the same layout of piers, using a non-self-supporting section.

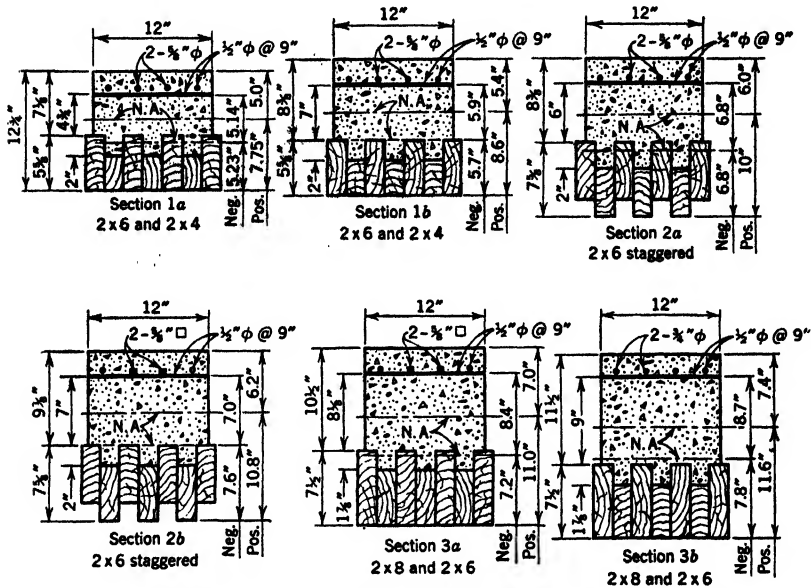


FIG. 5-13. Arrangements of Timber, Concrete, and Reinforcing Steel.

Suggested sections of the non-self-supporting type are shown in Fig. 5-13 and their properties in Table 5-3. For trial, section 1 b will be selected. Its resisting moments, from Table 5-3, are:

Positive— 324,000 in.-lb with respect to concrete

Negative—193,000 in.-lb with respect to steel

This section weighs 142.5 lb; hence the simple-span moment for dead load will be 192,375 in.-lb, which, distributed according to Table 5-1, is:

Positive— 105,800 in.-lb

Negative— 86,570 in.-lb

The live-load moments for the H-15 loading will be

Simple-span moment = 216,000 in.-lb

and distributed,

Positive— 162,000 in.-lb

Negative— 54,000 in.-lb

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The total moment, including thermal load, will be for interior spans:

Positive—  $105,800 + 162,000 + 22,100 = 289,900$  in.-lb

Negative—  $86,570 + 54,000 + 22,100 = 162,670$  in.-lb

whence

$$f_w \text{ positive} = 712 \text{ psi}$$

$$f_w \text{ negative} = 774 \text{ psi}$$

$$f_c^* = 1060 \text{ psi}$$

$$f_s^* = 16,740 \text{ psi}$$

TABLE 5-3. PROPERTIES OF SECTIONS

	Moment Inertia,  <i>I</i> in. <sup>4</sup>	Resisting Moment, in.-lb		Distance to Extreme Fiber <i>y</i> = in.		
Section		Concrete	Steel	Wood	Conc.	Steel
Mid-span Section—Positive						
1 <i>a</i>	2,700	270,000		7.7	5.0	
1 <i>b</i>	3,500	324,000		8.6	5.4	
2 <i>a</i>	4,565	383,000		10.0	6.0	
2 <i>b</i>	5,460	437,000		10.8	6.2	
3 <i>a</i>	7,650	545,000		11.0	7.0	
3 <i>b</i>	8,935	604,000		11.6	7.4	
Support Section—Negative						
1 <i>a</i>	911		170,000	5.2		5.1
1 <i>b</i>	1,195		193,000	5.7		5.9
2 <i>a</i>	1,510		214,000	6.8		6.8
2 <i>b</i>	2,010		275,000	7.6		7.0
3 <i>a</i>	2,715		311,000	7.2		8.4
3 <i>b</i>	3,295		364,000	7.8		8.7

$$\frac{E_c}{E_w} = n = 2 \quad \frac{E_s}{E_w} = n = 18.75$$

$$f_c = 1000 \text{ psi}$$

$$f_s = 18,000 \text{ psi}$$

$$f_w = \text{value assigned to grade used}$$

See Specifications for Prefabricated Panels.

For computing the reaction associated with shear, neglect the dead load within the height of the beam or slab from each end, place the concentrated load at three times the section depth or  $3d$  from the support, and compute the moment at this point. Thus:

\* Impact added to moments for computing these quantities.

$$\text{Dead-load reaction} = \frac{1}{2}(142\frac{1}{2} \times 27\frac{2}{3}) = 1971 \text{ lb}$$

$$\text{Live-load reaction} = \frac{26.5}{30} \times 3000 = 2650 \text{ lb}$$

Moments at points 3d from supports:

Dead-load moment

$$= (1971 \times 3\frac{1}{2} \times 12) - (2\frac{1}{3} \times 142\frac{1}{2} \times 14) = 78,127 \text{ in.-lb}$$

Live-load moment = 2650 × 42

$$= 111,300 \text{ in.-lb}$$

33⅓% impact allowance

$$= 37,100 \text{ in.-lb}$$

$$\text{Total} = 226,527 \text{ in.-lb}$$

$$\frac{226,527}{\frac{2}{3} \times 14} = 24,270 \text{ lb shear between 3d point and support}$$

$$\frac{24,270}{3.5} = 6950 \text{ nsf}$$

requiring 6950/1750 or 3.97 shear developers per square foot and 3.97/3.69 or 1.07 per foot per groove. Thus, an 11-in. spacing near support is indicated (Fig. 5-14).

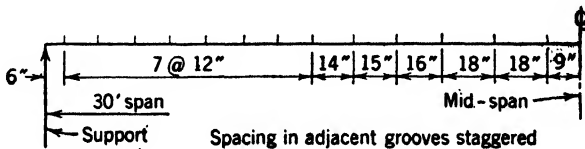


FIG. 5-14.

The foregoing does not take into account the fact that the shear developers are not located at the plane of maximum stress. The difference is neglected and contributes a desirable factor of safety.

There will be 26 shear developers in one row and 27 in every alternate row, making an average of 26.5 in each groove throughout the 30-ft span.

Estimate of quantities follows:

Treated timber:

$$111 \text{ pieces } 2 \times 6 = 111 \text{ FBM}$$

$$110 \text{ pieces } 2 \times 4 = 73.33$$

$$\text{Total} = 184.33 \text{ FBM}$$



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Reinforcement:

$$1.33 \times 34 \times 0.668 = 30.3 \text{ lb}$$

$$1.0 \times 30 \times 0.668 = 20.0 \text{ lb}$$

$$2 \times 13.5 \times 1.33 \times 1.043 = 32.85 \text{ lb}$$

---

$$83.15 \text{ plf}$$

Shear developers:

$$26.5 \times 3.69 = 97.8 \text{ pieces per linear foot}$$

Concrete:

$$\frac{10.5}{12} \times 30 \div 27 = 0.88 \text{ cu yd per linear foot}$$

Total quantities:

$$\text{Treated timber:} \quad 184.33 \times 228 = 42.00 \text{ MBM (1000 ft, board measure)}$$

$$\text{Reinforcement:} \quad 87.85 \times 228 = 20,025 \text{ lb}$$

$$\text{Shear developers:} \quad 97.8 \times 228 = 22,295 \text{ pieces}$$

$$\text{Concrete:} \quad 0.88 \times 228 = 200.8 \text{ cu yd}$$

In this case it appears that there would be little if any difference in cost between the self-supporting and non-self-supporting 30-ft-span layout. It is likely that the saving in treated lumber (see page 311) in the non-self-supporting type might be offset by the additional cost of the remaining items, including shear developers, steel, and concrete. However, under special conditions of extremely high costs or difficulty of obtaining one material compared to another, a different condition might result. The engineer must, of course, be governed by the special conditions prevailing.

### PRACTICAL CONSIDERATIONS

#### EXPANSION JOINTS

A true expansion joint in the composite construction must extend completely through both wood and concrete. An open space will be left between the expansion ends thus formed and its width will depend on the distance between such joints and on other factors dictated by the particular case under consideration. Probably expansion joints in the composite construction may be considerably farther apart, especially



FIG. 5-15. Grade Crossing near Haig, B. C., over Johnson Creek. Built on a 14-degree curve, it carries the Trans-Canada Highway over main line of the Canadian Pacific Railway. It has a creosoted laminated-timber-concrete deck and consists of 23 creosoted timber spans and one steel span, requiring 209,509 bd ft of creosoted Douglas fir.

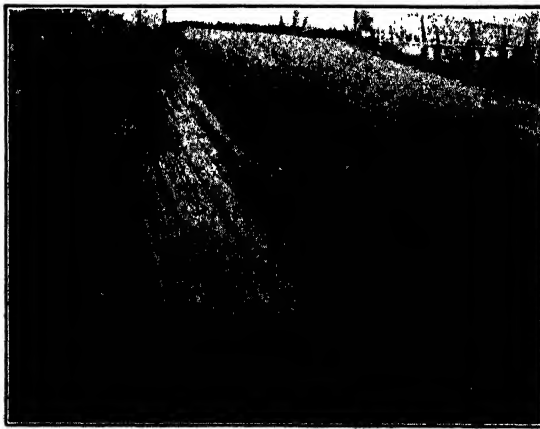


FIG. 5-16. Laying Laminated Subdeck on 8-degree Curve on Highway Bridge Crossing Tracks of Chicago, Milwaukee, St. Paul and Pacific Railroad at Savanna, Ill. Timbers were cut to length before treatment.

in the case of a timber-pile substructure, than is generally supposed. Reaches of 500 ft between expansion joints are common practice for pier structures, although a spacing of 250 to 300 ft has generally been used in the case of highway bridges.

The timber substructure itself gives considerable resiliency to the structure and may take up most, if not all, of the movement in the superstructure owing to temperature variation. This should be taken into consideration when a structure is designed, because expansion joints increase the difficulties of construction and result in additional "end spans" for which, of course, there is an increase in the intensity of both dead- and live-load stresses. There is also the difficulty of the variable-length laminations needed to accommodate the end-span construction. Where expansion joints are located at considerable distance apart, an excellent arrangement is to provide a double pier bent and permit the slab ends to cantilever over each way to the center between bents. There an open joint may be left without risk. The double bent may be thoroughly braced and provide an important measure of rigidity to the whole structure.

#### PLACING THE SHEAR DEVELOPER

It will not be practicable to drive the metal-shear developers directly into the wood subbase without prior preparation. All locations for shear developers first must be marked off on the subdeck, usually by means of a chalk line stretched across the deck. A chisel is then used to cut the slot for the shear developers at these points. The chisel suitably housed in a forged tool-steel shank as illustrated herewith has been found satisfactory and should invariably be used with a medium air hammer. When handled by an experienced crew, two men, one operating the hammer and the other following up by putting the shear developers in place and driving them home with a 4-lb sledge can place the shear developers at the rate of approximately 300 per hour. Experience indicates that a shear-developer slotting tool such as illustrated here will be sufficient to cut about 100,000 slots before needing replacement. In some instances, it has been found preferable to have the chisel blade welded in the forged shank rather than made fast by bolting. The chisel blade is, of course, precisely the same thickness as the shear developers themselves, thus cutting the slot into which the shear developers fit without play of any kind. The chisel is made of the best-grade heat-treated tool steel, similar to that used in the highest-grade circular lumber saws.



FIG. 5-17. Slots for Shear Developers Being Cut in Grooves.



FIG. 5-18. Shear Developers Being Placed in Laminated-Creosoted-Timber Base Prior to Driving Uplift Spikes and Placing Reinforcing. The arrangement of laminations and the pattern of shear developers are clearly shown.

## PREFABRICATION OF WOOD SECTIONS

It may be convenient to assemble the subdeck of the composite construction in panels about 12 in. wide in which the individual laminations are rigidly attached by means of spiral or threaded dowels placed



FIG. 5-19. View Taken during Construction of the Bridge Crossing Sowashee Creek near Meridian, Miss., Showing Portion of Creosoted Laminated Deck after Placing Shear Developers and Reinforcing Rods. Concrete mat being placed.

in holes of appropriate diameter. The pieces forming the panel are accurately assembled with enough "shop" dowels to insure its integrity. The panel will also be provided with holes arranged in pairs appropriately spaced so that, when assembled in the finished work, adjacent panels may be made fast to each other by means of the same type of dowels driven in the field. With the holes in pairs the field dowels will overlap one another, thus providing a continuous transverse tie throughout the entire width of the deck slab. Prefabricated panels will be placed in the structure in the same manner as would the individual laminations where prefabricated construction is not involved. Specifications for the placing of the subdeck under either system are included in the discussion. These have been found to be practical workable

specifications and should be employed where composite construction of this kind is indicated.

#### PLACING THE REINFORCEMENT

Following the placement of the shear developers, laying of the reinforcing bars or mesh will be next in order. Throughout most of the slab, the steel will serve primarily as temperature or shrinkage reinforcement while over the supports of continuous slabs additional reinforcing bars will be placed to provide for the negative stresses. In order to obtain the most effective arrangement, the so-called slab bars or those serving as shrinkage reinforcement should be centered over the supports and spliced at or near the mid-span points. The additional tensile reinforcing rods, usually about 0.45 span length, placed between the slab bars, should be staggered back and forth in the direction of span, maintaining a full steel section over the support, and avoiding an abrupt change of pattern at their extremities.

Frequently it may be found convenient, in forwarding the construction, to employ trucks, cranes, or other equipment on the subdeck as the construction proceeds. The composite construction is inherently of such flexible nature as to permit a variety of construction methods to expedite the progress of the work.

### SPECIFICATIONS

#### DECK LUMBER

All lumber shall be of the stress classification designated on the plans and in the specifications. It shall be surfaced four sides to standard dimensions. Lumber shall be graded in accordance with and finished dimensions shall conform to requirements of standard specification D245-37 for Structural Wood Joist and Plank, Beams and Stringers, and Posts and Timbers of the American Society for Testing Materials or the Standard Specification for Highway Bridges of the American Association of State Highway Officials.

**Treatment.** Lumber shall be treated with a minimum of 8 lb of Grade One creosote\* per cubic foot in accordance with the current specifications of the American Wood-Preservers' Association.

**Placing.** Pieces shall be placed in the structure with due regard, first, to securing full and accurate bearing on the supports for each individual piece. They shall then be brought to position by spiking, so as to maintain as nearly as possible, and without undue strain, the uniform depth of groove shown on the plans. A template block may be used for the purpose. Variation in depth of groove exceeding  $\frac{1}{8}$  in. within 5 ft of the supports shall not be permitted. An additional tolerance of  $\frac{1}{8}$  in. in depth of groove shall be permitted throughout the balance

\* For interior floors a standard salt treatment may be used.

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of the span. Filler blocks for the bearing of the elevated laminations on the supports, where required, shall be accurately placed and nailed only to the caps with two 30d nails, driven vertically.

**Spiking of Laminations.** Gage lines for horizontal spiking shall be carefully observed. Spikes in the upper gage line should be inclined slightly downward, and those in the lower gage line inclined slightly upward to prevent undue approach to the edges of the pieces. No protruding heads of spikes shall occur, but all shall be flush and well set.

### **SHEAR DEVELOPERS**

Shear developers shall be of structural-grade steel conforming to American Society for Testing Materials Standards, Serial A7-39. They shall be accurately manufactured to the dimensions shown on the plans and shall be free of any rough and uneven edges.

**Placing.** No slots shall be cut or shear developers placed until the deck timbers are all in place and completely spiked together. All slots for shear developers shall be cut by means of a tool approved by the engineer. In general, the tool shall consist of a steel or forged body in which a chisel blade is housed, with a suitable shank to fill a standard medium air hammer.

The chisel blade shall be of the best grade of heat-treated tool steel properly tempered to withstand driving under the blow of the hammer. In general, it should be of material similar to that in the highest-grade circular saws. It shall be the exact size and thickness of the shear developer, except that suitable provision for its attachment to the tool should be made. The blade shall be so placed in the housing that the slot can be cut to the full depth required for placing the shear developers.

The blade shall have cutting edges sharpened to a uniform angle on both sides, and care shall be taken to maintain constantly a keen sharp cutting edge. For this purpose the contractor should have available at all times extra blades, well sharpened, for replacing dull blades. Obviously, the tool should be so designed as to facilitate prompt changing of blades when or if necessary. After the slot has been cut, the shear developer shall be set in place and driven home with a sledge weighing not less than 4 lb, care being taken that it enters true and square, is thoroughly secure, and occupies the position shown on the plans.

### **PREFABRICATED PANELS**

**Boring of Holes in Lumber.** All pieces of lumber for assembly in panels shall be square end trimmed to the length shown in the plans. Each piece shall be bored separately, prior to preservative treatment, for both shop and field dowels. To insure accurate location of all holes, a drill jig, template, or other method or device shall be used so that all holes in any one piece will match all holes in all other pieces. There will be but a single gage line for all field dowel holes, and these must occur in a truly straight line from end to end of each piece. Holes for shop dowels may occur in more than a single gage line, and these shall be accurately bored, as shown on the drawings, so as to correspond with all holes for shop dowels in any other piece to be assembled in the same panel.

**Assembling Pieces in the Panels.** The work of assembling individual pieces of lumber into panels shall be done after the material has been preservatively treated. The several members specified on the drawings which are required to make one

panel shall be fastened together with the indicated number of shop dowels in the following manner: All pieces of a panel shall be carefully lined from end to end, bringing all holes to an accurate match, using not less than three pilot pins in the length of a panel to hold pieces in place. The pieces shall then be firmly held together by means of clamps or press while the shop dowels are driven. Driving of dowels shall preferably be done with pneumatic riveter or air hammer, but hand driving is not excluded. Pieces in a panel shall be so held and the dowels so driven as to result in an assembly of uniform width coming within the tolerance for panel width shown on the drawings. The work of assembling the pieces in panels shall preferably be done at the fabricating or treating plant, but may be done at the job site, providing suitable equipment for doing so, approved by the engineer, may be applied.

**Assembly of Panels in Subdeck.** The contractor may employ any method he chooses for assembling the panels in the deck of the structure as shown on the plans and subject to approval of the engineer. The field dowels for the center line or axis panels will be of a length equal to two panel widths and will be driven alternately in one hole of each pair from opposite sides. The holes remaining open will accommodate dowels protruding through from subsequently placed panels, to provide necessary lap. The position of expansion joints in the structure shall be observed and appropriate length panels used in end spans and those on either side of the joint. Regardless of the assembly plan, it will be necessary to line up the panels carefully for snug bearing against adjacent panels and to eliminate any local bulges which might impair the general alignment of the deck or leave objectionable openings between the panels.

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## Plastics-Based Laminates

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In the past decade there has been considerable interest in the use of laminated materials for structural purposes. In general, these consist of a multiplicity of sheets of fabric, paper, wood, or fibrous mat material which have been impregnated with a suitable resin and subsequently pressed with or without the application of heat. In the production of high-pressure laminates, fabric, paper, or other suitable material is passed through a solution of the resin. The resin content of the impregnated fabric is generally controlled by one of the following methods or combinations of them:

1. Squeeze rolls in which the pressure on the rolls can be varied or an adjustable doctor blade.
2. Control of the viscosity of the resin solution by the use of various combinations of solvents.
3. Control of the solids content of the resin solution.

The impregnated material is then passed through a drier operated at a sufficiently high temperature to evaporate all or any part of the solvents present and to polymerize the resin to such an extent that it will have the proper flow characteristics in the subsequent pressing operations. This partial polymerization or pre-cure of the resin results in removal of most of the water of condensation and lowers the moisture absorption of the material giving better electrical properties to the finished material. Phenolic-type resins are used to a large extent in the production of industrial laminates of all types where color is not of great importance and high arc resistance is not among the required electrical properties. Urea-formaldehyde resins are used quite extensively in decorative laminates with alpha cellulose paper as the reinforcing material. Melamine-formaldehyde resins are particularly

useful in laminates because of the unlimited color range possible, lower moisture absorption than urea formaldehyde and superior electrical properties. The fillers commonly used in the production of laminates are:

1. Lightweight cotton fabrics up to 4 oz per square yard in weight where good tensile strength and good finish are required in machined parts.

2. Heavyweight cotton fabrics, 4 to 40 oz per square yard in weight where mechanical properties such as impact strength are important, finish of machined surfaces is not important, and thick sections of the laminate are required.

3. Glass fabric and glass mats where heat resistance, excellent mechanical properties, and good electrical properties are of prime importance, cost being relatively unimportant.

4. Woven asbestos and asbestos paper where heat resistance and cost are important and in some applications where the relatively high modulus of elasticity of these materials can be used to advantage.

5. Rag, kraft, and alpha cellulose paper in the production of electrical grades of the phenolic laminates and in the production of decorative laminates.

6. Perforated metal foils in the production of certain types of cigarette-proof laminates used extensively for table tops and similar products.

7. Miscellaneous inorganic materials, such as graphite, mica, and alumina, in combination with the above to give special properties to the material.

In the manufacture of a typical cotton-fabric-reinforced general-purpose phenolic laminate the following process would be illustrative of the steps involved. An ammonia-catalyzed phenol-formaldehyde resin would be dissolved in alcohol, and the resulting solution would be adjusted in solids content to have a viscosity of 200–400 centipoises and at the same time allow the cloth used in the process to pick up a resin content of approximately 45 per cent. A typical fabric used in the process would have approximately the following properties:

Weight per sq yd	5.2 oz
Construction	68 × 32 threads per in. in warp and fill, respectively
Sizing	Gray goods contain starch sizing in warp only
Minimum tensile strength	70–40 lb per in. of width

This material would be dipped in the resin solution at atmospheric temperature and pressure and then passed into a continuous drier at

approximately 300°F, the temperature of the drier and the velocity of the material being adjusted to give the proper polymerization or flow to the resin and the proper volatile content. The flow or greenness characteristics of the resin would be determined by taking a number of small sheets of the material as it comes from the drier, pressing for a definite period of time at a definite temperature and pressure, removing the material from the press, breaking the resin from the edge of the molded piece and by means of weight measurements calculating the percentage resin that flowed beyond the edges of the fabric. The per cent of volatile matter in the material could be determined by heating a sample for a period of 15 min in an oven at 220°F and determining the loss in weight. After the velocity through the oven and the temperature had been adjusted to give the proper characteristics, the material being processed would be wound in rolls.

The rolls of coated material would be cut into sheets of the desired size, the size being determined by the desired characteristics of the finished laminate. If it were advantageous to produce a material having equal tensile strength in the cross direction and machine direction of the coated material, it would be necessary to adjust the size to that which would allow the sheets to be stacked in such fashion that the warp threads of alternate sheets were parallel. If this property were not required, or if more tensile strength were required in one sheet direction, the sheet could be cut to the required length and stacked with all warp threads parallel. In this particular case this would result in a laminate having approximately 75 per cent greater tensile strength in the machine direction than in the cross direction.

The proper number of sheets of cut material would be placed between polished metal platens, placed in a hydraulic press between steam-heated platens at approximately 340°F and approximately 1500 psi pressure for the required time. To produce a finished laminate 0.125 in. thick, the time required would be approximately 50 min. The material would then be cooled in the press by circulating cold water through the platens for a period of approximately 40 min. After removal from the press, the sheet would be trimmed to size. If a matte finish was desired, the surface might be lightly sanded, or other finishes might be applied by using properly finished metal press plates.

#### MECHANICS OF LAMINATES

Before one considers the mechanics of laminates, it might be advantageous to list the properties of a typical phenolic laminate reinforced with a heavy weave cotton fabric.

The data in Table 6-1 were obtained from samples tested and conditioned at 25°C and 50 per cent relative humidity, using the conditioning procedures and test methods of Federal Standard Stock Catalog LP 406.

TABLE 6-1. PROPERTIES OF TYPICAL PHENOLIC LAMINATE REINFORCED WITH HEAVY WEAVE COTTON FABRIC

Average Density 25°/4°	1.35 gm/cc			
Water Absorption 24 hr Immersion at 25°C	1.24%			
	1/8-in. Sample, psi		1/2-in. Sample, psi	
	Flatwise	Edgewise	Flatwise	Edgewise
Compressive strength	40,760		41,510	
Machine direction		23,320		
Cross direction				23,180
Modulus of elasticity				
In compression	660,140		657,800	
Machine direction				1,035,000
Cross direction				980,200
In tension				
Machine direction	1,069,000			
Cross direction	990,000			
In flexure				
Machine direction	1,106,000			1,083,600
Cross direction	981,730			1,048,500
Ultimate tensile strength				
Machine direction	11,300			
Cross direction	9,740			
Flexural strength				
Maximum fiber stress				
Machine direction	21,100			19,390
Cross direction	19,000			18,660
Ultimate shear strength				
Machine direction	12,930	14,060	14,110	14,900
Cross direction	12,280	13,350	14,100	14,490
Izod impact strength, ft-lb per in. of notch				
Flatwise, machine direction	4.47			
Cross direction	4.28			
Edgewise, machine direction	2.53			
Cross direction	2.40			
	1 cycle		10 <sup>6</sup> cycles	
Flexural fatigue strength	20,300 MD		4,050 MD	
Maximum fiber stress in psi to cause failure	18,999 CD		3,710 CD	

MD—Machine direction or warp direction of fabric.

CD—Cross direction or filler direction of fabric.

## EFFECT OF ELEVATED AND SUBNORMAL TEMPERATURES ON PHYSICAL PROPERTIES

As one might expect, the physical properties of laminates are affected by temperature. At elevated temperatures the compressive, tensile, flexural, bearing, and shear strengths decrease, whereas impact strength increases. At subnormal temperatures the converse is true. Table 6-2 gives the approximate magnitude of change that might be expected at temperatures of 160°F and -70°F as compared to values obtained at 25°C.

TABLE 6-2

Test	Property	Per Cent Change at	
		160°F	-70°F
Compression	Ultimate strength (edgewise)	-22	
	Modulus of elasticity	-25	
Tension	Ultimate strength	-18	
	Elongation at break	-6	
	Modulus of elasticity	-22	
Flexure	Maximum fiber stress	-24	+19
	Modulus of elasticity	-27	+33
Bearing	Stress at 4% deformation	-10	
	Ultimate strength	-20	
Shear	Ultimate strength	-16	
Impact	Energy to break	+24	-38

These changes in physical properties with temperature would hold only in the case of the type of material described. Other resins and reinforcing materials might be expected to behave differently, but some idea of their behavior might be obtained from a study of comparative thermal properties.

## NEMA GRADES

A wide variety of laminates are available today; however, most applications can be taken care of by those materials which are classed as standards by the National Electrical Manufacturers Association. The following description of the various types and their properties is taken from the August 1946 Standards for Laminated Thermosetting Products published by the National Electrical Manufacturers Association.

**Paper Base Grades****GRADE X**

*Sheets.* Primarily intended for mechanical applications where electrical properties are of secondary importance. Should be used with discretion when high humidity conditions are encountered. Not equal to fabric base grades in impact strength.

*Tubes, Rolled.* Good punching and fair machining qualities. Low power factor and high dielectric strength under dry conditions.

*Tubes, Molded.* Better in moisture resistance and machining qualities than Grade X rolled. Strongest paper base except in thin walls. Dielectric strength may be low at molded seams.

*Rods.* This grade is not made in this form.

**GRADE P**

*Sheets.* Primarily intended for punching. More flexible and not quite so strong as Grade X. Moisture resistance and electrical properties intermediate between Grades X and XX.

*Tubes and Rods.* This grade is not made in these forms.

**GRADE XX**

*Sheets.* Suitable for usual electrical applications. Good machinability.

*Tubes, Rolled.* Good machining, punching, and threading qualities. Not so strong mechanically as Grade X rolled but better moisture resistance. Better grade for low dielectric losses, particularly on exposure to high humidity.

*Tubes, Molded.* Better in moisture resistance than Grade XX rolled or than X grades. Good machining and good electrical properties, except in very thin walls where the dielectric strength may be low at the molded seams.

*Rods.* Similar characteristics to sheet except as limited by the inherent differences in construction and shape.

**GRADE XXP**

*Sheets.* Similar to Grade XX in electrical and moisture-resisting properties but more suitable for hot punching. Intermediate between Grades P and XX in punching and cold-flow characteristics.

*Tubes and Rods.* This grade is not made in these forms.

**GRADE XXX**

*Sheets.* Suitable for radio-frequency work, for high humidity applications, and with minimum cold-flow characteristics.

*Molded Tubes and Rods.* Similar characteristics to sheet except as limited by the inherent differences in construction and shape.

**GRADE XXXP**

*Sheets.* Similar to Grade XXX but having lower dielectric losses and being more suitable for hot punching. This grade has greater cold flow than Grade XXX and is intermediate between Grades XXP and XXX in punching characteristics.

*Tubes and Rods.* This grade is not made in these forms.

**Fabric Base Grades****GRADE C**

*Sheets.* Made throughout from cotton fabric weighing over 4 oz per square yard and having a count as determined from inspection of the laminated plate of not more than 72 threads per inch in the filler direction nor more than 140 threads per inch in both warp and filler directions. A strong tough material suitable for gears and other applications requiring high impact. The heavier the fabric base used the higher will be the impact strength, but the rougher the machined edge; consequently, there may be several subgrades in this class adapted for various sizes of gears and types of mechanical service. Should not be used for electrical applications except for low voltages.

*Tubes, Rolled.* Made from a cotton fabric with the same weight and thread-count limits as for sheets of this grade.

*Tubes, Molded.* This grade not standardized in this form.

*Rods.* Made from a cotton fabric with the same weight and thread-count limits as for sheets of this grade. Characteristics in general same as for sheet except as limited by the inherent differences in construction and shape.

**GRADE CE**

*Sheets.* Made of same fabric weight and thread-count limits as Grade C. For electrical applications requiring greater toughness than Grade XX or mechanical applications requiring greater resistance to moisture than Grade C. Exceptionally good in moisture resistance.

*Tubes, Rolled.* This grade not standardized in this form.

*Tubes, Molded.* Made of same fabric weight and thread-count limits as Grade C sheet. For use where a tough dense fabric-base material is required, having fair electrical properties along with excellent mechanical properties and good resistance to moisture. Dielectric strength may be low at molded seams, especially in thin walls.

*Rods.* Characteristics same as for molded tubes except as limited by the inherent differences in construction and shape.

**GRADE L**

*Sheets.* Made throughout from cotton fabric weighing 4 oz per square yard or less. As determined by inspection of the laminated plate, the minimum thread count per inch in any ply shall be 72 in the filler direction and 140 total in both warp and filler directions. For purposes of identification, the surface sheets shall have a minimum thread count of 80 threads per inch in each of the warp and filler directions. This grade is suitable for small gears and other fine machining applications, particularly in thicknesses under  $\frac{1}{2}$  inch. Not quite so tough as Grade C. Should not be used for electrical applications, except for low voltage.

*Tubes, Rolled.* This grade not standardized in this form.

*Tubes, Molded.* Made from fine-weave cotton fabric weighing 4 oz per square yard or less. As determined by inspection of the molded tube, the minimum thread count per inch shall be 72 in the filler direction and 140 total in both warp and filler directions. Has high density and good moisture resistance. For mechanical applications primarily where finer machined appearance than with Grade



CE molded is desired or where tougher material than Grade LE molded is required. Should not be used for electrical applications, except for low voltage.

*Rods.* Similar in count and weight of fabric to Grade L molded tube; also in general characteristics except as limited by the inherent differences in construction and shape.

#### GRADE LE

*Sheets.* Made of fabric of same weight and thread-count limits as Grade L sheet. For electrical applications requiring greater toughness than Grade XX. Better machining properties and finer appearance than Grade CE, also available in thinner sizes. Exceptionally good in moisture resistance.

*Tubes, Rolled.* Made from fabric of same weight and thread-count limits as Grade L molded. Best concentricity and dielectric strength of any fabric-base grade. For use where the seams from a molded tube may be objectionable and where the application requires good machining qualities, together with good electrical and mechanical properties.

*Tubes, Molded.* Made from a fine-weave cotton fabric of the same weight and thread-count limits as Grade L molded. Has excellent machining and moisture-resisting characteristics. For use in electrical applications even under humid conditions where a tougher material than Grade XX tubing is required at some sacrifice of electrical properties. Dielectric strength may be low at molded seams, especially in thin walls. Better electrically than Grade CE molded, but not quite so tough.

*Rods.* Similar in count and weight of fabric to Grade LE molded tube, also in general characteristics except as limited by inherent differences in construction and shape.

#### LP2-16 Asbestos Base Grades

##### GRADE A

*Sheets.* Asbestos paper base. More resistant to flame and slightly more resistant to heat than other laminated grades because of high inorganic content. Suitable only for low-voltage applications. Minimum dimensional changes when exposed to moisture.

*Tubes, Rolled and Molded.* Similar in characteristics to sheet except as limited by the inherent differences in construction and shape.

*Rods.* Similar in characteristics to sheet except as limited by the inherent differences in construction and shape.

##### GRADE AA

*Sheets.* Asbestos fabric base. More resistant to heat and stronger and tougher than Grade A. Suitable only for low-voltage applications. Minimum dimensional changes when exposed to moisture.

*Tubes, Rolled and Molded.* Similar in characteristics to sheet except as limited by the inherent differences in construction and shape.

*Rods.* Similar in characteristics to sheet except as limited by the inherent differences in construction and shape.

**LP2-17 Glass Base Grades****GRADE G-1**

Staple-fiber-type glass cloth. General-purpose, heat-resisting grade.

**GRADE G-2**

Staple-fiber-type glass cloth. Good electrical properties under high humidity conditions. Electrical and heat-resisting grade.

**TABLE 6-3. STANDARD AND AVERAGE MECHANICAL PROPERTIES OF LAMINATED THERMOSETTING SHEET**

Grade	Type of Value	Tensile Strength, psi	Flexural Strength, psi	Compression Strength, psi (Flatwise)	Isod Impact Strength— Ft-Lb/1-In. Notch	
					Flatwise	Edgewise
X	Minimum standard	10,000	20,000	.....	1.3	0.50
	Average value	14,000	23,000	35,000	....	....
P	Minimum standard	6,000	11,000	.....	....	0.50
	Average value	8,000	15,000	22,000	....	....
XX	Minimum standard	8,000	12,000	.....	1.0	0.40
	Average value	9,000	16,000	34,000	....	....
XXP	Minimum standard	6,000	12,000	.....	....	0.40
	Average value	8,000	16,000	25,000	....	....
XXX	Minimum standard	6,000	12,000	.....	0.80	0.35
	Average value	7,000	15,000	32,000	....	....
XXXXP	Minimum standard	5,000	12,000	.....	....	0.30
	Average value	7,000	15,000	25,000	....	....
C	Minimum standard	7,500	16,000	35,000	3.2	2.0
	Average value	9,500	20,000	38,000	....	....
CE	Minimum standard	6,500	13,000	34,000	2.3	1.3
	Average value	8,000	17,000	36,000	....	....
L	Minimum standard	7,000	15,000	30,000	2.5	1.2
	Average value	9,000	20,000	35,000	....	....
LE	Minimum standard	6,500	15,000	33,000	1.8	1.0
	Average value	8,500	19,000	37,000	....	....
A	Minimum standard	5,000	10,000	30,000	1.8	0.80
	Average value	8,000	16,000	36,000	....	....
AA	Minimum standard	8,000	16,000	35,000	3.5	3.0
	Average value	10,000	20,000	38,000	....	....

All values are based on tests at room temperature of approximately 25°C (77°F). The above standards are for sheets in thicknesses of  $\frac{1}{16}$  to 1 in., inclusive. The minimum standards for mechanical properties for sheets from more than 1 to 2 in., inclusive, shall be 10 per cent lower than those given in this table.

Flatwise impact tests are applicable only to sheets having a thickness of  $\frac{1}{2}$  in. or over and machined to  $\frac{1}{4}$  in. in thickness. No flatwise values are given for Grades P, XXP, or XXXP as these grades are not available in thicknesses exceeding  $\frac{1}{4}$  in.

**GRADE G-3**

Continuous-filament-type glass cloth. General-purpose grade.

**GRADE G-4**

Glass-mat type. Good electrical properties under high humidity conditions. Moderate heat resistance. Best punching quality of the G grades.

TABLE 6-4. LP2-74 STANDARD AND AVERAGE DIELECTRIC-STRENGTH VALUES OF LAMINATED THERMOSETTING SHEET

Grades X, P, XX, XXX	Type of Test	Type of Value	Dielectric Strength Perpendicular to Laminations, volts per mil									
			$\frac{1}{16}$ - $\frac{1}{8}$ in. Incl.	$\frac{1}{8}$ - $\frac{1}{4}$ in. Incl.	Over $\frac{1}{4}$ - $\frac{1}{2}$ in. Incl.	Over $\frac{1}{2}$ - $\frac{3}{4}$ in. Incl.	Over $\frac{3}{4}$ -1 in. Incl.	Over 1-2 in. Incl.				
XXX, XXXP	Short time	Minimum standard	700	500	360	250	180	145	130	90		
	Step by step	Average value	950	700	500	360	250	205	180	130		
		Minimum standard	450	300	220	150	110	90	80	55		
		Average value	700	500	360	250	180	145	130	90		
C	Short time	Minimum standard	700	500	360	250	180	145	130	90		
	Step by step	Average value	900	650	470	340	240	200	175	120		
		Minimum standard	450	300	220	150	110	90	80	55		
		Average value	650	450	320	225	165	135	115	85		
L	Short time	Minimum standard	...	...	...	...	...	...	...	...		
	Step by step	Average value	...	200	150	100	75	60	50	35		
		Minimum standard	...	...	...	...	...	...	...	...		
		Average value	...	120	90	60	45	35	30	20		
CE	Short time	Minimum standard	...	...	...	...	...	...	...	...		
	Step by step	Average value	250	200	150	100	75	60	50	35		
		Minimum standard	...	...	...	...	...	...	...	...		
		Average value	150	120	90	60	45	35	30	20		
LE	Short time	Minimum standard	...	...	...	...	...	...	...	...		
	Step by step	Average value	...	400	290	200	145	120	105	75		
		Minimum standard	...	...	...	...	...	...	...	...		
		Average value	...	500	360	250	180	145	130	90		
A	Short time	Minimum standard	...	...	...	...	...	...	...	...		
	Step by step	Average value	...	240	170	120	85	70	60	40		
		Minimum standard	...	...	...	...	...	...	...	...		
		Average value	...	300	220	150	110	90	80	55		
AA	Short time	Minimum standard	560	400	290	200	145	120	105	75		
	Step by step	Average value	700	500	360	250	180	145	130	90		
		Minimum standard	350	240	170	120	85	70	60	40		
		Average value	450	300	220	150	110	90	80	55		
AA	Short time	Minimum standard	...	...	...	...	...	...	...	...		
	Step by step	Average value	...	225	160	110	80	65	55	40		
		Minimum standard	...	...	...	...	...	...	...	...		
		Average value	...	135	95	65	50	40	35	25		
8	Short time	Minimum standard	...	...	...	...	...	...	...	...		
	Step by step	Average value	...	...	50	35	25	20	18	13		
		Minimum standard	...	...	...	...	...	...	...	...		
		Average value	...	...	30	20	15	12	10	8		

Values for Grades P, XXXP, and XXXP are applicable only up to  $\frac{1}{4}$  in. thickness, inclusive, since these grades are not made in the heavier thicknesses.

## GRADE G-5

Continuous-filament-type glass cloth, melamine binder. General-purpose grade. Good arc and flame resistance.

TABLE 6-5. LP2-76 STANDARD AND AVERAGE DIELECTRIC-LOSS PROPERTIES OF LAMINATED THERMOSETTING SHEET

Grade	Type of Value	Power Factor, 10 <sup>6</sup> cycles/sec	Dielectric Constant, 10 <sup>6</sup> cycles/sec	Loss Factor, 10 <sup>6</sup> cycles/sec
X, P	Maximum standard	.....	...	....
	Average value	0.060	6.0	0.36
XX	Maximum Standard	0.045	5.5	0.25
	Average value	0.040	5.0	0.20
XXP	Maximum standard	0.045	5.5	0.25
	Average value	0.040	5.0	0.20
XXX	Maximum standard	0.035	5.2	0.18
	Average value	0.032	4.8	0.15
XXXXP	Maximum standard	0.030	5.2	0.16
	Average value	0.027	4.5	0.12
C	Maximum standard	.....	...	....
	Average value	0.10	7.0	0.70
CE	Maximum standard	0.065	6.0	0.40
	Average value	0.055	5.5	0.30
L	Maximum standard	.....	...	....
	Average value	0.10	7.0	0.70
LE	Maximum standard	0.055	5.5	0.30
	Average value	0.045	5.0	0.22
A, AA	Maximum standard	.....	...	....
	Average value	.....	...	....

The above values cover all thicknesses up to 1 in., inclusive, and are based on tests on specimens in the as-received condition measured at room temperature of approximately 25°C (77°F).

**PHYSICAL AND ELECTRICAL PROPERTIES OF GRADES OF  
LAMINATED SHEET, TUBING, AND ROD**

## VALUES

For a number of properties two sets of values are given:

1. Average values.
2. Minimum or maximum standards.

*Average values* represent the average of the values in the lengthwise and crosswise direction taken over a number of tests and serve as a

basis for comparison between each grade and other grades or materials.

*Minimum standards* (for mechanical properties and dielectric strength) and *maximum standards* (for water absorption, power factor, dielectric constant and dielectric loss) serve as a basis for acceptance and rejection and for design purposes.

TABLE 6-6. LP-2-80 STANDARD PROPERTIES OF LAMINATED THERMOSETTING TUBING

Grade	Size, Inside by Outside Diameters in.	Minimum Density,* grams/cm <sup>3</sup>	Minimum Tensile Strength, psi	Minimum Compressive (Axial), psi	Minimum Dielectric Strength Perpendicular to Laminations, volts per mil	
					Short-Time Test	Step-by-Step Test
X rolled	1 x 1½	1.10	7,500	10,000	500 †	300 †
XX rolled	1 x 1½	1.10	7,000	12,000	400	250
X molded	1 x 1½	1.25	9,000	15,000	400	250
XX molded	1 x 1½	1.25	7,500	15,000	300	200
C rolled	1 x 1½	1.10	5,500	11,000	None	None
LE rolled	1 x 1½	1.10	5,000	11,000	150	100
LE rolled	1 x 1¼	1.10	5,000	11,000	150	100
CE molded	1 x 1¼	1.25	6,500	19,000	175	100
L molded	1 x 1½	1.25	6,500	18,000	None	None
L molded	1 x 1¼	1.25	6,500	18,000	None	None
LE molded	1 x 1½	1.25	6,000	19,000	150	90
LE molded	1 x 1¼	1.25	6,000	19,000	175	110

Grade	Material as Received						
	Maximum Water Absorption, per cent	Maximum Power Factor, 10 <sup>6</sup> cycles/sec	Maximum Dielectric Constant, 10 <sup>6</sup> cycles/sec	Maximum Loss Factor, 10 <sup>6</sup> cycles/sec	Maximum Power Factor, 10 <sup>6</sup> cycles/sec	Maximum Dielectric Constant, 10 <sup>6</sup> cycles/sec	Maximum Loss Factor, 10 <sup>6</sup> cycles/sec
X rolled	5.0	0.040	5.0	0.20	0.070	6.0	0.42
XX rolled	2.5	0.040	5.0	0.20	0.055	6.0	0.33
X molded	4.0	0.045	6.0	0.26	0.070	7.5	0.52
XX molded	2.0	0.040	5.5	0.22	0.055	6.5	0.35
C rolled	...	...	...	...	...	...	...
LE rolled	...	...	...	...	...	...	...
LE rolled	...	...	...	...	...	...	...
CE molded	...	...	...	...	...	...	...
L molded	...	...	...	...	...	...	...
L molded	...	...	...	...	...	...	...
LE molded	...	...	...	...	...	...	...
LE molded	...	...	...	...	...	...	...

\* These density values apply to all sizes of tubing.

† The high dielectric strength of Grade X rolled tubing is only obtainable under dry conditions. Under high humidity the dielectric strength of this grade is low.

### Variation in Properties with Form

Because of inherent differences in shape, structure, and method of manufacture neither physical and electrical test methods nor properties will be the same for rods, tubing, or sheets of the same grade.

## FACTOR OF SAFETY

As with other structural and insulating materials, good engineering practice demands an adequate factor of safety. Using the standard properties for the various grades, a minimum factor of safety of 4 for mechanical strength and 6 for dielectric strength are recommended for best design.

TABLE 6-7. LP2-90 STANDARD PHYSICAL AND MECHANICAL PROPERTIES OF LAMINATED THERMOSETTING ROD

Grade	Diameter, in.	Minimum Density, grams per cm <sup>3</sup>	Minimum Tensile Strength, psi	Minimum Flexural Strength, psi	Minimum Compressive Strength (Axial) psi
XX	½ to 1, incl.	1.30	8,500	15,000	20,000
	Over 1 to 2, incl.	1.30	6,500	12,000	20,000
XXX	½ to 1, incl.	1.25	8,000	13,000	20,000
	Over 1 to 2, incl.	1.25	6,000	11,000	20,000
C	¼ to ½, incl.	1.28	7,500	17,000	20,000
	Over ½ to 1, incl.	1.28	8,000	17,000	20,000
	Over 1 to 2, incl.	1.28	6,500	14,000	20,000
CE	¼ to ½, incl.	1.26	6,500	12,000	21,000
	Over ½ to 1, incl.	1.26	7,000	14,000	21,000
	Over 1 to 2, incl.	1.26	6,000	12,000	21,000
L	⅜ to 1, incl.	1.28	8,000	16,000	20,000
	Over 1 to 2, incl.	1.28	6,500	13,000	20,000
LE	⅜ to 1, incl.	1.26	6,000	12,000	21,000
	Over 1 to 2, incl.	1.26	4,800	9,000	21,000
A	¼ to ½, incl.	1.55	7,000	10,000	15,000
	Over ½ to 1, incl.	1.55	6,000	10,000	15,000
	Over 1 to 2, incl.	1.55	5,000	9,000	15,000
AA	½ to 1, incl.	1.45	6,000	11,000	19,000
	Over 1 to 2, incl.	1.45	5,500	9,000	19,000

## Standards Set for Certain Properties Only

In the interest of simplicity for both consumer and manufacturer, standards for any one grade are only for those properties which have proved susceptible to manufacturing control and which are essential to the major applications of the grade. For example, for the timing or rolling-mill gears neither the manufacturer nor consumer is interested

in the electrical properties of the gear but rather in its mechanical properties. In fact, good electrical properties cannot be obtained without some sacrifice in mechanical strength. Furthermore, the best electrical properties can only be obtained with considerable loss in mechanical properties, particularly toughness or impact strength.

### Laminated Thermosetting Sheet—Variation in Properties with Thickness

For tensile, flexural, and compressive strength of laminated thermosetting sheet the minimum standards given for each grade will be held for thicknesses of  $\frac{1}{16}$  to 1 in. Minimum standards for thicknesses of 1 to 2 in. are 10 per cent lower. The average values for thicknesses of  $\frac{1}{8}$  in. and under will generally be higher than the figures given, whereas the average values for thicknesses approaching 1 in. will be as much as 10 per cent lower than those given.

TABLE 6-8. ASTM METHOD

Test	Sheet	Tubes	Rods
Tensile strength	D 229	D 348	D 349
Compressive strength	D 229	D 348	D 349
Flexural strength	D 229	.....	D 349
Impact strength	D 229	.....	.....
Water absorption	D 229	D 348	D 349
Density	.....	D 348	D 349
Dielectric strength	D 229	D 349	.....
Power factor	D 150	D 150	.....
Dielectric constant	D 150	D 150	.....
Loss factor	D 150	D 150	.....
Dimensions	D 229	D 668	D 741
Warp	D 709	D 668	D 741

In Tables 6-3 to 6-7 are given values of the physical properties of the various grades. These are taken from the publications of the National Electrical Manufacturers Association.

### TEST METHODS FOR PHYSICAL AND ELECTRICAL PROPERTIES OF LAMINATED THERMOSETTING SHEET, TUBING, AND ROD

#### LP2-100 Test Methods for Sheet, Tubing and Rod

All values given are based on the test methods of the American Society for Testing Materials except where otherwise noted. In all cases the value reported shall be the average of the values determined for the number of specimens required by the specific test method. The latest published revisions or changes in ASTM methods shall auto-

matically apply. Latest revisions will be found in the ASTM Book of Standards, Part III, Non-Metallic Materials—General, and its Annual Supplements.

The values in the tables in these standards are based on specimens tested as received and under room conditions of  $25^{\circ}\text{C} \pm 1^{\circ}\text{C}$  and prevailing laboratory humidities, except for impact tests. Impact tests are to be conducted on specimens conditioned for 48 hr at  $50^{\circ}\text{C}$  in a circulating-air oven, and then cooled to room temperature  $25^{\circ}\text{C} \pm 1^{\circ}\text{C}$ . The methods indicated in Table 6-8 should be used.

### COMPREG

Compreg is a laminate consisting of resin-impregnated wood veneers bonded together and highly compressed during the curing cycle.

TABLE 6-9. STRENGTH PROPERTIES OF BIRCH COMPREG \*

Property	Value
Tension, psi	
Stress at proportional limit	22,000
Maximum strength	32,000
Modulus of elasticity	3,500,000
Flexure, psi	
Stress at proportional limit	21,000
Modulus of rupture	36,000
Modulus of elasticity	3,500,000
Compression parallel to grain, psi	
Stress at proportional limit	16,000
Modulus of rupture	24,000
Modulus of elasticity	3,500,000
Johnson double shear, parallel to grain and perpendicular to laminations, psi	7,000
Izod impact, ft-lb/in.	5 to 9
Face-notched	4 to 7
Edge-notched	

\* Parallel laminated with specific gravity of 1.35.

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Of the many resins tried, the most successful have been water-soluble phenol-formaldehyde resinoids. Resorcinol may be employed in place of phenol but is more costly. Urea gives less dimensional stability. Resins sufficiently advanced to require straight alcohol as a solvent penetrate and bond with the wood less satisfactorily, although some resins requiring a solvent of mixed water and alcohol give generally satisfactory dimensional stability with less embrittlement.



Impregnation of green or dry veneers is by steeping (veneers  $\frac{1}{16}$  in. or thinner), by pressure tank (25–100 psi for 15 min to 5 hr), or by combined vacuum and pressure. Generally about 30 per cent resin solids by weight of dry wood is retained when the solution contains about 35 per cent resinoid. The dried veneers are laid up, either parallel-laminated or cross-banded, placed in a hot plate press, and pressed and cured at 1000 to 3000 psi and 285–310°F. Time under pressure, depending on thickness, may range from 10 min to 2 hr.

TABLE 6-10. EFFECT OF DIFFERENT PRESSURES AND RESINS ON PROPERTIES OF BIRCH COMPREG

Number	Item	Resin A *			Resin B †		Resin C ‡
		204	205	206	207	208	
1	Panel number						
2	Molding pressure, psi	1,500	600	1,500	800	1,500	600
3	Specific gravity	1.36	1.22	1.36	1.24	1.37	1.24
4	Tension modulus psi $\times 10^{-6}$	4.12	3.72	4.20	3.92	4.23	3.88
5	Tension strength, psi	53,700	43,600	54,600	43,500	51,300	47,900
6	Compression modulus, psi $\times 10^{-6}$	4.21	3.81	4.17	4.07	4.33	3.94
7	Compression strength, psi	24,200	22,700	26,800	25,200	24,500	22,800
8	Compression yield strength at 0.2 per cent offset, psi	20,700	19,000	21,900	21,000	21,600	19,900
9	Torsion (shearing) modulus, psi $\times 10^{-6}$	0.289	0.248	0.337	0.298	0.306	0.251
10	Modulus of rupture (torsion), psi	6,720	5,060	9,800	6,980	8,400	5,180
11	Shearing (torsion) yield strength at 0.2 per cent offset, psi	5,100	4,180	7,720	5,700	5,880	4,850
12	Shear strength parallel to laminations, psi	4,840	3,640	4,450	4,230	4,340	3,620
13	Impact, ft-lb per in. of notch	10.0	8.3	7.8	6.1	9.4	6.6
14	Fatigue strength at $10^7$ cycles, psi	11,800	11,800	13,400	12,000	12,000	10,600
15	Water absorption, per cent	3.0	7.0	1.7	5.0	2.0	6.7
16	Swelling, per cent	14.2	13.9	9.7	9.9	11.5	12.2
17	Recovery, per cent	2.90	2.97	1.87	2.22	2.28	2.00

ASME Trans. (May 1946), pp. 317–327.

\* Alcohol-soluble.

† Water-soluble.

‡ Water-soluble.

The specific gravity is generally between 1.3 and 1.4. Strength and other properties are largely dependent on the specific gravity and on the proportions of resin and wood; the species of wood is less important if the final specific gravity is the same for specimens made from different species.

A variant of compreg is unimpregnated thin veneers (usually less than  $\frac{1}{32}$  in.) interwoven with resin film or coated with resin solution, compressed and cured in a manner similar to compreg. Dimensional stability is usually less than that of compreg, but impact strength is greater and embrittlement less.

TABLE 6-11. COMPOSITION, MODULUS OF RUPTURE, AND FATIGUE LIMITS OF VARIOUS TYPES OF COMPREG AND COMPRESSED WOOD LAMINATES

Type	Veneers		Composition	Bonding			Specific Gravity	Bending Modulus of Rupture, psi	Fatigue Limit	
				Time, Min	Temperature, °F	Pressure, psi				
A	1/2-in. maple, 60 ply		Phenolic-resin film	30	300	2,500	1.40	26,100	Modulus of Elasticity, psi	Per Cent Modulus of Rupture
B	1/4-in. birch, 60 ply		Phenolic-resin film	30	300	2,500	1.41	41,100	2,730,000	10,500
C	1/8-in. birch, 35 ply		Phenolic-resin film	30	300	2,500	1.39	47,500	2,710,000	11,950
D	1/8-in. birch, 35 ply, cross-banded		Phenolic-resin film	30	300	2,500	1.36	29,900	3,710,000	13,500
E	1/2-in. maple, 20 ply		Medium-polymer phenolic coating	30	300	1,500	1.38	34,000	2,290,000	7,500
F	1/2-in. birch, 20 ply		Medium-polymer phenolic coating	30	300	1,500	1.40	32,700	2,800,000	10,200
G	1/2-in. maple, 20 ply		Medium-polymer phenolic coating	30	350	1,500	1.36	26,800	2,750,000	9,180
H	1/2-in. maple, 20 ply		Low-polymer A, 25 per cent impregnation	30	300	1,500	1.37	33,100	2,360,000	7,780
J	1/2-in. maple, 20 ply		Low-polymer A, 42 per cent impregnation	30	300	1,500	1.37	31,400	3,020,000	12,600
K	1/2-in. maple, 9 ply		Low-polymer B, impregnated	30	320	2,800	1.33	37,600	2,710,000	11,950
L	1/2-in. birch, 15 ply		Low-polymer C, impregnated	45	304	1,050	1.32	39,800	3,010,000	10,900

ASTM Bul. 129 (Aug. 1944), 31-34.

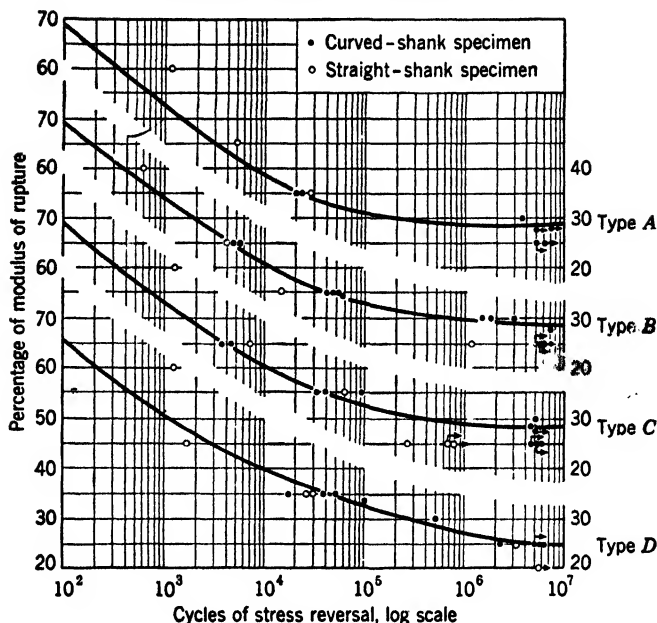


FIG. 6-1.  $S-N$  Curves for Phenolic-Resin-Film Bonded and Compressed Materials. (Courtesy American Society for Testing Materials)

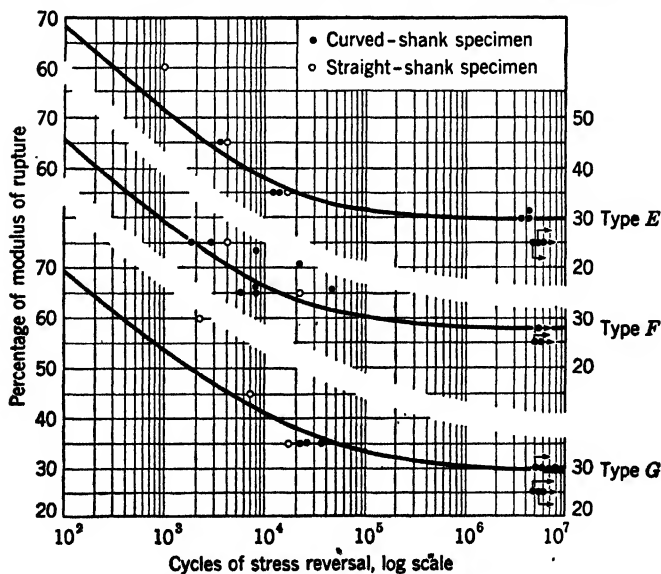


FIG. 6-2.  $S-N$  Curves for Medium-Polymer Phenolic Solution Bonded and Compressed Materials. (Courtesy American Society for Testing Materials)

Various investigators have reported physical and mechanical properties. Tables are drawn from these sources. The most extensive American investigations have been carried out by the U. S. Forest Products Laboratory.

The effects of two different curing pressures and three different resins on various properties are listed in Table 6-10.

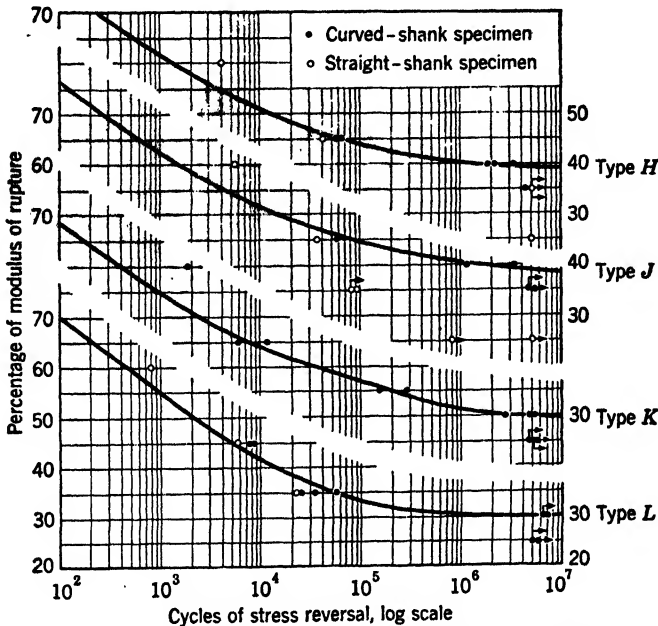


FIG. 6-3. *S-N* Curves for Low-Polymer Phenolic Resin Impregnated and Compressed Materials. (Courtesy American Society for Testing Materials)

Fatigue studies have been made on a number of types of Compreg because this material has been extensively employed for aircraft propellers. The results of one series made on rotating-beam specimens at constant bending moment are summarized in Figs. 6-1, 6-2, and 6-3, and in Table 6-11.

#### AVTEX \*

Laminates of wood veneer and resin or of woven cloth and resin have limitations particularly in forming, but also in physical properties which in a construction such as Avtex are overcome (Table 6-12).

\* This section was contributed by the Hood Rubber Co., Watertown, Mass., a division of the B. F. Goodrich Co.

By using cotton fiber in a lap form, carefully cleaned and treated directly with a solution of a phenolic resin, it is possible to obtain superior homogeneity and to preserve much of the inherent strength of the individual cotton fiber.

The impregnated cotton web is dried by passing around a heated drum and then through a drying tunnel. As it emerges from this tunnel, it can be plied up or cut and cross-plyed as desired. For certain uses, exterior faces of veneer can be attached and hence make it possible to glue the part for attachment to other surfaces.

TABLE 6-12. PHYSICAL PROPERTIES OF AVI

	(1) Balanced Structure			(2) Fibers Parallel		
	1.36			1.36		
Specific gravity						
Tensile, psi	-80°F	+70° to 76°F	+160°F	-80°F	+70° to 76°F	+160°F
Parallel to length	19,000	20,900	12,000	28,000	27,000	18,000
At 90°	15,000	20,700	12,500	8,000	6,000	4,500
At 45°	20,000	17,900	12,000	10,000	8,000	6,000
Block compression, psi		50,150			27,000	
Reduction in thickness during compression		11%			15%	
Bearing, psi		35,300			24,000	
Flexural, psi						
Parallel		27,000			34,000	
At 90°		28,200			10,000	
At 45°		22,200			14,000	
Impacts (Isod-Notched), psi						
Parallel		17.4			.....	
At 90°		17.0			.....	
At 45°		20.0			.....	
Modulus of elasticity in Tension, psi		1,230,000			1,700,000	
Hardness, Rockwell M Scale		100			100	
Shear, psi (punching)		15,000			14,000	
Shear, psi (cylindrical)		13,200			.....	
Thermal conductivity						
Btu/sq in./°F/in./hr		1.04			1.94	
Thermal Expansion per °F						
Parts per million						
Range, -40°F to 100°F		12.0			.....	
Moisture absorption		1.8%			1.8%	
Flammability		Self-extinguishing			Self-extinguishing	

Compression of the laminate in a heated hydraulic press produces a strong dense attractive sheet or an irregularly-shaped molded article as may be desired.

The weight-strength factor was of considerable value in aircraft construction during the war.

Due to the fiber content and consequent moisture absorption, this material is not recommended where outstanding electrical properties

are necessary. It is much less absorbent than impregnated-wood laminates and is little affected by common acids, bases, and other chemicals.

### GENERAL CONSIDERATIONS

Since laminates are composite structures combining the properties of the resin and reinforcing material, the strength properties may be ex-

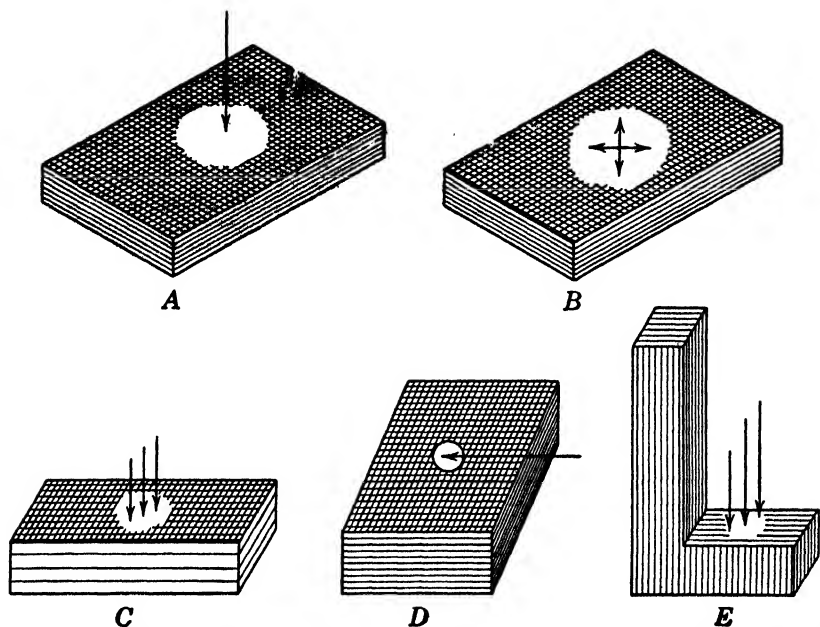


FIG. 6-4. A. Compressive Loads, B. Tensile Loads, C. Flexural Stress, D. Bearing Stresses, E. Shear Loads.

pected to vary in the different directions with respect to the plane of the laminations, directional properties of the fabric or other reinforcing material. These observations will be confirmed by a study of the physical properties of a typical laminate and emphasize the necessity of taking advantage of them where possible in the design of structures to be made of laminates. Figure 6-4 shows how directional loads may be applied to laminates with respect to these properties.

The properties of the finished laminate are influenced to a large extent by the properties of the resin, the reinforcing material and the character of the bond between the two. The tensile strengths of several typical fibers are:

	Psi
Cellulose Monofilament *	26,600
Cotton *	40,000
Manila hemp *	116,000
Glass fibers (0.00023 in. diam.) †	200,000
Glass fibers (0.00002 in. diam.) †	3,500,000

\* International Critical Tables.

† *The New Fibers* by Sherman & Sherman, D. Van Nostrand Company, N. Y.

Laminates made from these fibers should show tensile strength properties roughly proportional to

1. The tensile strength of the fiber.
2. The percentage of fiber present in the direction in which the load is applied.
3. The contribution of the resin to the tensile strength.
4. The efficiency of the bond between resin and fiber.

Very little work has been done on the interfacial properties of resins and fibers, but the importance of these relationships cannot be overestimated. If one assumes that it is possible to make a laminate in which all the fibers are oriented in one direction and bonded to each other in such fashion that the load applied is equally distributed among the fibers, such a laminate containing approximately 50 per cent fibers, and 50 per cent resin should have a tensile strength of better than 1,000,000 psi when made from fibers having a diameter of approximately 0.00002 in. In this ideal case it would also be desirable to have a resin with elastic and thermal properties (modulus of elasticity and coefficient of expansion) similar to those of the fibers. The functions of the resin in this ideal case would be to

1. Fill completely the space between individual fibers.
2. Distribute any load equally among all fibers.
3. Protect the fibers from external influences.

This ideal resin would of course be very limited in application since it could only be used with the specific type and size of fiber for which it was formulated. In general the properties of fibers vary over wide ranges in their physical properties. In the case of glass and some vegetable fibers the tensile strength is a function of the diameter; the smaller the diameter the higher the tensile strength in pounds per square inch. Some fibers tend to absorb the resin and others do not, and so larger percentages of resin are required to bond efficiently absorbent fibers than nonabsorbent fibers of equal diameter. Some tend

to absorb moisture which causes a change in their physical and dimensional properties; however, when they are treated with the proper resin these changes are limited in their extent. Typical classes of resins used by the laminating industry along with their advantages and disadvantages are discussed in the following paragraphs.

#### TYPES OF RESINS

*Phenol-formaldehyde resins* are widely used in the laminating industry where color is of little importance, both one-stage alkaline-catalyzed and two-stage acid-catalyzed resins being used. The advantages of phenolic resins are:

1. Low cost.
2. Low flammability.
3. Good mechanical properties.
4. Fair electrical properties.

In most cases the fabric or other material to be impregnated is treated with an alcohol solution of the resin; however, in veneers and woods where it is important to reach a high degree of saturation of wood with resin low molecular weight, water-soluble or water-dispersible resins have been used.

*Urea-formaldehyde resins* are used to a large extent in the manufacture of decorative laminates where color is of major importance. Their advantages and disadvantages are:

##### Advantages

1. Available in all colors.
2. Good electrical properties when not exposed to moisture.
3. Resistance to organic solvents.

##### Disadvantages

1. Rather poor water resistance.
2. Low resistance to acids and alkalis.
3. Rather poor aging characteristics.

*Melamine-formaldehyde resins* have recently been widely used in the manufacture of glass-base laminates because of their ability to withstand relatively high temperatures and because of the high impact strength of laminates having glass cloth as the reinforcing material.

##### Advantages

1. Ability to withstand relatively high temperature.
2. Good arcing and tracking resistance.
3. High impact resistance with glass-fiber fillers.
4. Available in a wide range of colors.

##### Disadvantages

1. High cost.
2. Relatively high moisture absorption.



TABLE 6-13. PHYSICAL PROPERTIES OF CAST ALLYL RESINS AND LAMINATES BONDED WITH ALLYL RESINS

Property	Cast Resins					
	C.R. 10	C.R. 38	C.R. 39	C.R. 41		
Barrel hardness	49	21	21	0		
Barrel cold flow	2	4	11	0		
Tensile strength, psi	12,000	12,000	9,500	880		
Flexural strength, psi	680,000	380,000	300,000	4,900		
Compressive strength, psi	23,600	27,050	22,100	3,000		
Impact strength, unnotched						
1 ind. ft.-lb./in.	0.9	1.0	2.1	6.7		
Water absorption, per cent						
24 hr at 25°C	0.2	0.3	0.2	0.8		
168 hr at 25°C	0.2	0.6	0.8	1.9		
4 hr at 100°C	0.7	0.8	0.7	2.8		

Laminates with No. 360 Cotton Sheet						
Property	Longitudinal		Transverse		Longitudinal	
	C.R. 10	C.R. 38	C.R. 39	C.R. 41	Transverse	Transverse
Barrel hardness	49	45	31	0		
Barrel cold flow	3	6	3			
Tensile strength, psi	10,400	9,500	10,500	5,800	6,200	2,200
Flexural strength, psi	15,600	17,800	18,900	5,900	150,000	5,600
Compressive strength, psi	22,100	570,000	620,000	150,000	.....	350,000
Impact strength, notched						
1 ind. ft.-lb./in. of notch	1.9	2.0	1.2	2.0	1.3	2.9
Water absorption, per cent						
24 hr at 25°C	0.6	0.8	1.2	4.5		
168 hr at 25°C	1.5	1.9	2.9	6.4		
4 hr at 100°C	1.2	1.5	3.0	5.7		

Laminates with ECC-11-148 Fiberglass						
Property	Longitudinal		Transverse		Longitudinal	
	C.R. 10	C.R. 38	C.P. 39	C.R. 41	Transverse	Transverse
Barrel hardness	53	41	5	0		
Barrel cold flow	4	5				
Tensile strength, psi	39,600	40,700	37,300	27,400	34,400	18,500
Flexural strength, psi	.....	17,000	16,500	4,200	18,000	4,200
Compressive strength, psi	.....	1,480,000	1,260,000	310,000	1,630,000	280,000
Impact strength, notched						
1 ind. ft.-lb./in. of notch	14.8	16.7	15.7	25,400	16.0	12.9
Water absorption, per cent						
24 hr at 25°C	0.5	0.9	0.8	2.7		
168 hr at 25°C	0.6	1.5	1.0	2.8		
4 hr at 100°C	0.4	1.5	0.8	2.8		

*Polyester resins* formed by the condensation of polybasic acids and polyhydric alcohols are used extensively in the production of low pressure and contact laminates. In the production of these resins the acid, the alcohol, or both contain reactive double bonds so that after the reinforcing material has been impregnated further polymerization can take place, resulting in the formation of a strong three-dimensional polymer. The last stage in this process is usually accomplished at low temperatures with the aid of a peroxide catalyst. Since extremely low pressures are used in the final cure, inexpensive molds can be used and the size of the laminated part is limited only by the size of the curing oven available.

TABLE 6-14. PHYSICAL PROPERTIES OF CAST ALLYL RESINS AND LAMINATES BONDED WITH ALLYL RESINS

Property	C.R. 38	C.R. 39	C.R. 39 Bd	C.R. 140
Cast Resins				
Barcol hardness	45	21	31	36
Barcol cold flow	4	11	8	4
Flexural strength, psi	12,000	9,500	20,100	13,200
Flexural modulus, psi	380,000	300,000	471,000	330,000
Compressive strength, psi	27,050	22,100	26,700	23,600
Impact strength, unnotched Izod, ft-lb/in.	1.0	2.1	3.5	1.0
Water absorption, per cent				
24 hr at 25°C	0.3	0.2	0.2	0.2
168 hr at 25°C	0.6	0.8	0.7	0.5
4 hr at 100°C	0.8	0.7	3.5	0.6
Laminates with ECC-11-128 Fiberglas				
Barcol hardness	49	.....	.....	47
Barcol cold flow	4	.....	.....	4
Tensile strength, psi	44,400	41,500	49,400	42,900
Flexural strength, psi	23,800	22,000	28,700	24,400
Flexural modulus, psi	1,950,000	1,750,000	2,080,000	2,080,000
Compressive strength, psi	55,300	60,000	63,100	58,000
Impact strength, notched Izod, ft-lb/in. of notch	23.2	23	24.6	20.0
Water absorption:				
24 hr at 25°C	0.3	0.4	0.6	0.4
168 hr at 25°C	0.7	0.9	.....	1.0

Table 6-13, 6-14, and 6-15 give the physical properties of typical laminates made from various types of fabrics and resins derived from allyl alcohol (data from *Modern Plastics*, June 1943, pages 102-104).

TABLE 6-15. PROPERTIES OF C.R. 39 LAMINATES

77°F except Where Otherwise Indicated

Property	Kraft Paper		8 Oz. Duck	
	Longitudinal	Transverse	Longitudinal	Transverse
Specific gravity		1.387		1.369
Tensile strength, psi	21,600	10,700	9,000	7,200
Flexural strength, psi	22,600	17,400	14,100	13,100
Flexural modulus, psi	1,190,000	780,000	420,000	360,000
Compressive strength, psi		31,400		29,200
Impact strength, notched				
Izod, ft-lb/in. of notch	0.91	0.61	3.2	2.1
Water absorption, per cent				
Weight change		3.9		1.54
Length change		0.0		0.00
Width change		0.0		0.00
Thickness change		1.5		0.00
Bonding strength, psi	255	226	429	370
	Hurlbut 716 Paper		Mitscherlich Paper	
	Longitudinal	Transverse	Longitudinal	Transverse
Specific gravity		1.402		1.414
Tensile strength, psi	12,200	11,200	25,600	10,400
Flexural strength, psi	18,400	16,800	25,800	16,400
Flexural modulus, psi	940,000	810,000	2,090,000	815,000

Compressive strength, psi	31,800			29,200			
Impact strength, notched							
Izod, ft-lb/in. of notch	1.0		0.98	1.1		0.90	
Water absorption, per cent							
Weight change		2.36			8.5		
Length change		0.13			0.13		
Width change		0.31			0.10		
Thickness change		0.69			0.18		
Bonding strength	287		294	166		167	
	Fiberglas OC-63		Fiberglas ECC-11-148		Cast C.R.		
	Longitudinal	Transverse	Longitudinal	Transverse	39		
Specific gravity		1.872		1.736		1.315	
Tensile strength, psi	76,400	800	37,800	32,000		5,000-6,000	
Flexural strength, psi	59,000	2,000	24,600	25,400		9,500	
Flexural modulus, psi	4,040,000	850,000	1,480,000	1,180,000		280,000-350,000	
Compressive strength, psi		15,000		48,000		22,100	
Impact strength, notched							
Izod, ft-lb/in. of notch	23.9	10.0	25.0	15.7		0.31	
Water absorption, per cent							
Weight change		0.22		0.85		0.24	
Length change		0.40		0.13		0.07	
Width change		0.00		-0.40		0.00	
Thickness change		0.58		0.00		0.25	
Bonding strength, psi	217	198	286	266			

**ENGINEERING PROPERTIES**

*Density.* Most of the phenolic laminates having either cotton cloth or paper as the reinforcing material have specific gravities in the range of 1.3 to 1.4, those having mineral fillers such as fiber glass or asbestos are in the range of 1.5 to 1.8. The melamine laminates have slightly higher specific gravities, usually 6 to 10 per cent higher than the phenolics. Recently sandwich-type materials \* have been produced by bonding a skin of relatively dense high-strength material such as glass fabric or metal to a low-density core of foamed thermoplastic material or a specially constructed core of high-strength material in which the construction is such that the finished core material contains up to approximately 95 per cent voids. Most of these materials use either a contact-type resin or solvent-type cement as the bonding agent. Depending on the type of core material used and the thickness of the skin, these materials can be produced with specific gravities as low as 0.05.

*Tensile and Flexural Properties.* The tensile and flexural strengths of industrial laminates seem to be closely related and are proportional to the tensile properties of the reinforcing material. The tensile strengths of paper- and cotton-fabric-reinforced materials vary from approximately 5000 to 20,000 psi. Flexural strengths of these materials show approximately the same range of values. Glass-fiber-reinforced materials have been prepared having tensile strengths up to 50,000 psi. The modulus of elasticity in tension of the paper- and cotton-fabric-reinforced materials is usually in the range of 1,000,000 to 2,000,000 psi, and for the glass-fiber-reinforced materials the modulus approaches a value of approximately 3,000,000 psi. Moduli of elasticity for the same materials in flexure have approximately the same values.

*Compressive Strength.* The compressive strength in the flatwise direction of most of the high-pressure laminates is to a large extent dependent on the compressive strength of the resin. The compressive strengths of most commercial laminates are in the range of 20,000 to 50,000 psi.

*Impact Strength.* Industrial laminates are available in an extremely wide range of impact strengths. Some of the paper-reinforced materials have impact strengths as low as 0.5 ft-lb per inch of notch, while some

\* See Chapters 1, 20, and 22 for more extended discussions of sandwich-type materials.

of the melamine-glass-fiber combinations approach 40 ft-lb per inch of notch.

*Flexural Fatigue Strength.* Considerable data are available in the literature on the flexural fatigue strength of laminates, particularly on those laminates used in aircraft such as laminated wood. Up to approximately 2,000,000 reversals of stress a plot of the logarithm of applied stress versus the logarithm of the number of reversals of stress usually is a straight line; beyond this limit the curve tends to flatten out. Data on two types of phenolic laminates reinforced with cotton fabric show a flexural fatigue strength (at constant stress) at 10,000,000 cycles of approximately 20 per cent of the flexural strength of the material.

*Dielectric Constant.* In general, the phenolic laminates have a dielectric constant in the as-received condition of 4.8 to 7.0. This is an indication of the properties of the material as compared to the dielectric properties of a vacuum under the same conditions. Those materials having high moisture absorption tend to increase in dielectric constant when exposed to conditions of high humidity.

*Power Factor.* Under as-received conditions the phenolic laminates have power factors from 0.1 to 0.027. Power factor is indicative of the relationships between the angular displacement of the vectors representing voltage and current when an a-c field is applied to the material.

*Loss Factor.* Loss factor is indicative of the electrical efficiency of the material; the lower the loss factor the more desirable the material as a dielectric. The loss factor of the standard grades of phenolic laminates usually varies from approximately 0.1 to 0.7.

*Dielectric Strength.* The dielectric strength of a material in volts per mil times the thickness of the material in mils gives the voltage required to puncture the material under specified conditions. As the thickness of the material in mils increases, the dielectric strength in volts per mil decreases.

#### POST FORMING OF LAMINATED PLASTICS\*

Laminated plastics can be shaped into simple bends and contours by the post-forming process. Grade-C type material employing a fabric-base core, bonded with phenol-formaldehyde resins, is best adapted to

\* This material was prepared by Mr. Frank Sullivan of the Formica Insulation Co., Cincinnati, Ohio.

shaping by this technique. Bends ranging from  $\frac{1}{32}$  in., depending on the thickness of stock, and draws of 50 per cent are possible. Paper-base materials of both industrial and decorative types can be worked under the same conditions but to less severe dimensions.

The post-forming technique can best be illustrated by breaking it down into separate operations. They are:

1. Cutting the flat sheet to the desired shape.
2. Heating the material to a formable condition.
3. Shaping in a suitable form.
4. Cooling.

In order to heat a sheet to a formable condition, a heat source of approximately 500°F is required. The heat may be secured through the use of several different media. Radiant heat from infrared bulbs; circulating and noncirculating hot air; contact with a hot plate; and immersion in hot oil, in a salt bath, or in molten metals have all been used successfully. The choice of heating media will depend to a great extent on the facilities available and to the type of forming setup required. The part to be formed should be heated as rapidly as possible to secure maximum pliability and yet not so rapidly as to cause blistering of the surface before the center of the sheet reaches a formable condition (see Fig. 6-5). Overheating of the material will cause blistering whereas underheating will reduce formability.

Laminates available for post forming may be divided roughly into two classes: industrial and decorative materials.

Of the industrial materials both fabric-base and paper-base are available. Fabric-base material is capable of being bent and drawn to a much greater extent than paper-base stock. The extent of formability of fabric-base industrial stock is shown in Table 6-16. The physical and electrical properties correspond to NEMA Grade C materials. These properties do not change substantially during the forming operation (Table 6-17).

Paper-base industrial material can be bent to radii of approximately  $\frac{1}{2}$  in. Drawing of this material is limited when compared to fabric base owing to the paper structures.

Decorative materials to be used in postforming operations are of two types: veneer stock and decorative types. Veneer stock for application to plywood or other suitable backing materials can be formed to a minimum radius of  $\frac{1}{2}$  in. in the  $\frac{1}{16}$ -in. thickness. These materials are available in black, solid colors, and printed designs. Decorative

materials designed for use without veneer operation but requiring some backing structure are constructed by surfacing Masonite with a standard decorative pattern. Bends to radii, ranging from 3 in. with the surface on the inside of the bend to 8 in. with the surface on the outside of the bend are possible.

TABLE 6-16. EXTENT OF FORMABILITY

Thickness, in.	Minimum Bending Radius, in.
$\frac{1}{32}$	$\frac{1}{32}$
$\frac{1}{16}$	$\frac{3}{32}$
$\frac{3}{32}$	$\frac{3}{16}$
$\frac{1}{8}$	$\frac{5}{16}$
$\frac{3}{16}$	$\frac{3}{8}$
$\frac{1}{4}$	1
$\frac{3}{8}$	$2\frac{1}{4}$
Depth of Draw, in.	
$\frac{1}{16}$	1
$\frac{3}{32}$	$1\frac{3}{16}$
$\frac{1}{8}$	$\frac{5}{8}$

Simple dies constructed of hardwood, laminated plastics, Masonite, or metal may be used to shape the part when it is in a heated state.

TABLE 6-17. PHYSICAL TESTS ON CJP-11

	Before Forming		After 5% Elongation	
	Warp	Filler	Warp	Filler
Tensile strength, psi	9,000	8,500	10,500	9,000
Modulus of elasticity in tension, psi	900,000	900,000	1,000,000	1,000,000
Impact strength (120 Izod)				
Ft-lb per in. notch				
Flatwise	3.6	2.9	3.3	2.8
Edgewise	2.8	2.6	2.6	2.4
Flexural strength, psi				
Flatwise	19,500	18,700	21,000	20,500
Edgewise	19,000	18,500	20,000	19,750
Water absorption				
Per cent gain in 24 hr				
$3'' \times 1'' \times \frac{1}{16}''$	2.7		3.4	
$3'' \times 1'' \times \frac{1}{8}''$	1.7		2.5	

Bends in one plane can be made using simple hinged forms or with vertically closing male and female dies (Fig. 6-6). Normally the forces required for simple bending are small enough that the forms may be manually operated. Handles of various kinds can be used to supply



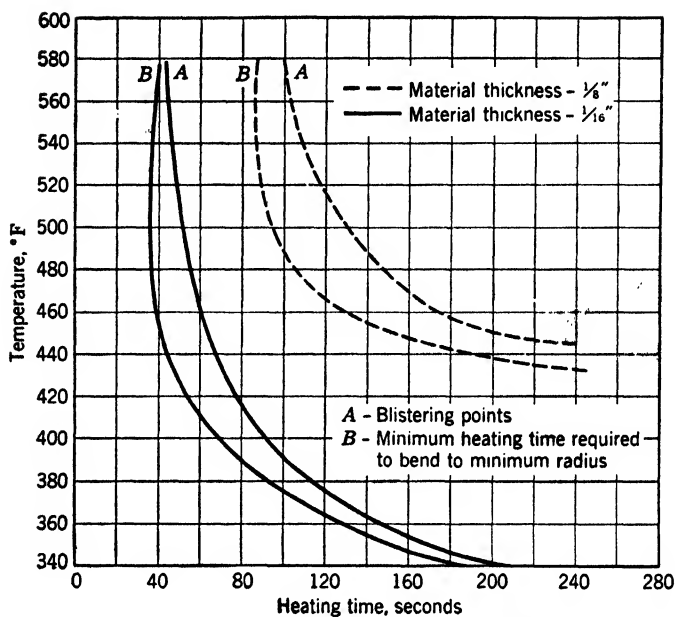


FIG. 6-5. Time-Temperature Relationships in Postforming of Laminates.

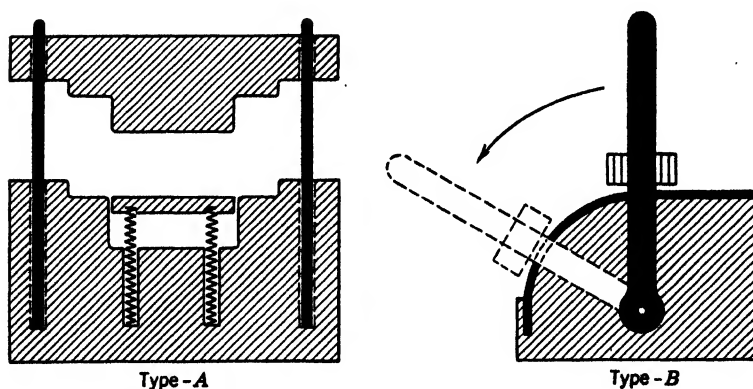


FIG. 6-6. Diagrammatic Representation of Techniques Employed in Postforming of Laminates.

the leverage necessary, and simple fastening devices will hold the form in place. For more intricate parts, guides or pins will be needed to insure exact placement in the form.

Drawing operations require tools which are somewhat similar to those used in drawing metal in that a hold-down plate and a positive means of controlled pressure are needed (Fig. 6-7). Hardwood or

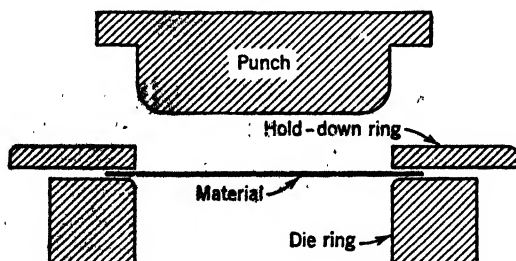


FIG. 6-7. Schematic Arrangement of Punch, Hold-Down Ring, Material, and Die Ring in Postforming of Laminates.

laminated plastic is usually sufficient for the drawing form unless the quantities involved amount to several thousands. For quantity production, it is usually advisable to use metal construction or a combination of wood or laminated plastics with metal inserts at wearing points. The pressure needed to form a part in which draws are to be encountered will depend to a great extent on the size, thickness of stock, and type of forming operation. Approximately 50 psi are normally sufficient for any forming operation.

After the forming jig or die has been closed, the piece is usually left in the form until it will retain the desired shape after removal. If metal forming tools are used, fins may be incorporated or the sections made thin enough so that ample cooling will be obtained using circulated air. If necessary, forms of this type may be cooled by circulating water through the form. When using wood, plastic, or composition forms, it is normal practice to resort to no forced cooling, but to provide enough forms so that 3 to 5 min. may elapse from the time of closing the form to the removal of the formed product. Depending on the shape of the part, it may be possible to remove the piece after about 30 sec and place it in a cooling frame where the heat may be dissipated more freely into the air. If a short time is allowed for the form to cool before reloading, there is rarely a condition of overheating. This may be facilitated by directing a stream of air over the form.

**THE FINISHED PART**

Parts produced by post forming are held to the NEMA grade-C tolerances for sheet stock of the same thickness. Wall thickness cannot be adjusted from the sheet thickness which is supplied.



**Fig. 6-8. Carrier and Tray Used in Handling Operations in Manufacture of Nylon Hosiery.. (Courtesy Formica Insulation Company)**

The material cost of laminated sheet when compared to metal is much greater based on either weight or thickness. Fabrication costs, based on studies made in the aircraft industry, are somewhat in favor of plastic materials. Dies and molds for post forming are relatively inexpensive compared to those required for working metals; however, this is minimized where quantity production is involved. An application which can utilize a postformed part cannot compare favorably

when cost alone is considered but must utilize some of the fundamental characteristics of laminated plastics.

The quantity applications up to the present time have been somewhat limited, with aircraft, electrical appliances, hosiery mills, railway club and dining cars, and taxicabs consuming the bulk of production. Field tests, however, are being conducted in many industries, and indications are that as more experience is gained under actual production conditions the scope of applications will broaden.

Analysis of production items indicates that the following general classifications incorporate the important contributions of post forming to the field of laminated plastics:

1. Incorporation of strengthening members by indenting portions of a flat sheet.
2. Simple bends in one or more planes, with elimination of corners by fabrication.
3. Draws in combination with strengtheners and simple bends (see Fig. 6-8).

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## Thermostat Metals

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### INTRODUCTION

The subject covered by this chapter is known variously as bimetal, thermometal, thermostatic bimetal, thermostatic metal, or thermostat metal. The first of these terms describes the material as being composed of two metals although as explained further there is no restriction regarding dual combinations. The plurality of components thus brings this type of material within the classification of engineering laminates. The other terms which contain the expression "thermostat" indicate the general field of application of these materials. Originally they were used as the temperature-sensitive elements of devices for controlling, regulating, or indicating temperature. "Thermostat Metals" \* have since been utilized in a great variety of ways, in any way in which a change in temperature could be used to control, regulate, compensate, indicate, and the like. A partial list of uses follows:

Air dryers	Candy mixers
Air heaters	Carburetor temperature regulators
Air valves	Chicken brooders
Alarm devices	Cigar lighters
Altitude meters	Circuit breakers
Aquarium heaters	Clocks
Automatic chokes	Cord sets
Automatic exhaust heat control	Damper controls
Blueprint machines	Demand indicators
Bread-wrapping machines	Dental furnaces

\* "Thermostat Metal" as a standard descriptive term for these materials has been accepted by The American Society for Testing Materials and is used throughout this section.

Dental sterilizers	Ovens, electric and gas
Draft controls	Percolators
Electric-light plants	Photomounting machines
Electric meters	Popcorn machines
Electric motors	Portable electric tools
Fans	Radiator shutters
Fire alarms	Ranges, electric and gas
Fluorescent starters	Recording thermometers
Gasoline gage indicators	Refrigerators
Gas safety pilots	Relays, overload
Glue pots	Relays, signal
Hat stretchers	Room thermometers
Heating pads	Room thermostats
Hot beds	Scales
Humidifiers	Shock absorbers
Incubators	Signal devices
Instruments, electric	Sign flashers
Instruments, testing	Soldering irons
Ironing machines	Stack controls
Irons, electric	Starting devices
Laboratory ovens	Steam radiators
Lamps, electric	Steam traps
Lamps, therapeutic	Time switches
Light flashers	Toasters, electric
Lighting systems	Transformer temperature indicators
Machine tools	Type-metal pots
Motor protection	Voltage regulators
Necktie pressers	Waffle irons
Oil-burner control	Water heaters, electric and gas
Oil gages	Windshield defrosters
Oil purifiers	

## DEFINITION

After this introduction thermostat metal can be defined as a composite metal usually in the form of sheet or strip, comprising two or more metals which, by virtue of the differing expansivities of its components, tends to change its curvature when subjected to a uniformly distributed change in temperature.

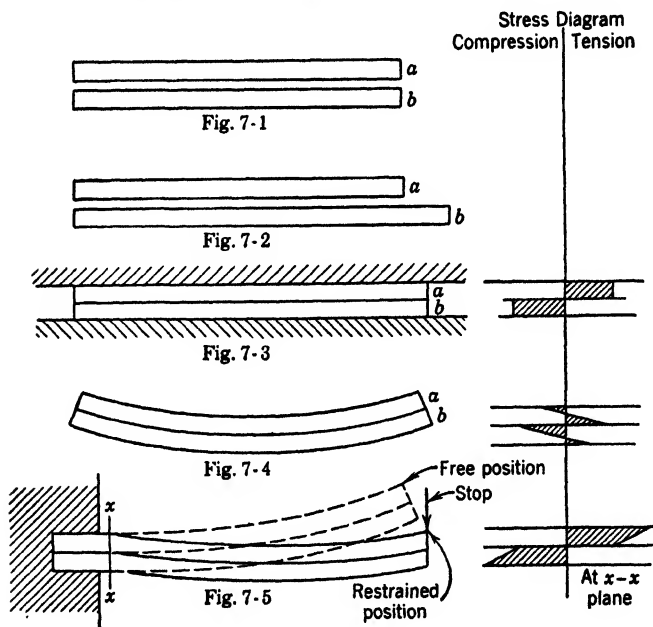
## HISTORY

Thermostat metal has been in use for a long time, for as early as 1766 it was suggested for use for temperature compensation in chronometers. Breguet's thermoscope (a combination of gold, silver, and platinum) invented in 1817, Ure's thermostat of brass and iron patented in 1831, Wilson's U. S. patent 24,896 of 1858 (brass and steel) are early recorded instances of its use. Villarceau in 1863 published an analysis

of its characteristics in the *Annales de l'Observatoire Impérial de Paris*. Since that time references occur with increasing frequency until in 1897 C. E. Guillaume and C. Dumas applied for a patent on an anomalous alloy of 36 per cent nickel and 64 per cent iron which later became known as Invar. The discovery of this alloy with its nearly zero coefficient of thermal expansion sparked the development of the large variety of present-day commercial thermostat metals which use it or variations for their efficient characteristics.

## PRINCIPLES UNDERLYING THERMOSTAT METAL ACTION

Before the various types of thermostat metals are described, the principles underlying the bending of a thermostat metal strip with a



FIGS. 7-1 to 7-5. Brief Diagrammatic Explanation of Thermostatic Action and Stress Patterns under Various Conditions.

change in temperature will be discussed. To illustrate the bending, consider two metal strips *a* and *b* (Fig. 7-1) having low and high coefficients of thermal expansion (henceforth called expansivities), respectively, and having identical dimensions. When the temperature is raised, their relative lengths will be as in Fig. 7-2. If the two are



bonded together, clamped as in Fig. 7-3, and then the temperature is raised, the one with the high expansivity will be under uniform compression, and the one with the low expansivity will be under uniform tension. These forces produce a bending moment, and, when the clamps are released, the free element will assume a uniform arc (Fig. 7-4). If the combination is straight or has an initial uniform curvature, the resulting curvature on uniform temperature change is uniform, that is, a true arc of constant radius. This follows since the stresses producing the bending moment are uniform for any cross section.

#### GENERAL EQUATION FOR BENDING OF THERMOSTAT METAL STRIP

The bending of thermostat metal strip when uniformly heated is mathematically described by the following equation: <sup>1</sup>

$$\frac{1}{\rho} = \frac{6(\alpha_2 - \alpha_1)(t_1 - t_0)(1 + m)^2}{h \left[ 3(1 + m)^2 + (1 + mn) \left( m^2 + \frac{1}{mn} \right) \right]} \quad (7-1)$$

where  $\alpha_1$  and  $\alpha_2$  = temperature coefficients of expansion (expansivities)

$E_1$  and  $E_2$  = moduli of elasticity

$d_1$  and  $d_2$  = thicknesses of components

$h$  = thickness of strip

$\rho$  = radius of curvature of strip

$t_1$  and  $t_0$  = temperatures

$$\frac{d_1}{d_2} = m, \quad \frac{E_1}{E_2} = n \quad (7-2)$$

If the thicknesses of both metals are the same,

$$d_1 = d_2, \quad m = 1$$

and

$$\frac{1}{\rho} = \frac{24(\alpha_2 - \alpha_1)(t_1 - t_0)}{h \left( 14 + n + \frac{1}{n} \right)} \quad (7-3)$$

Further, if the moduli of elasticity are the same,

$$E_1 = E_2, \quad n = 1$$

and

$$\frac{1}{\rho} = \frac{3(\alpha_2 - \alpha_1)(t_1 - t_0)}{2h} \quad (7-4)$$

## Equation for Bending of Thermostat Metal Strip 355

The radius of curvature is thus directly proportional to the difference in the expansivities and the temperature change and inversely proportional to the thickness of strip. The radius of curvature is affected by the ratio of moduli of elasticity of the components. Which component has the larger modulus is immaterial as long as the ratio is the same.

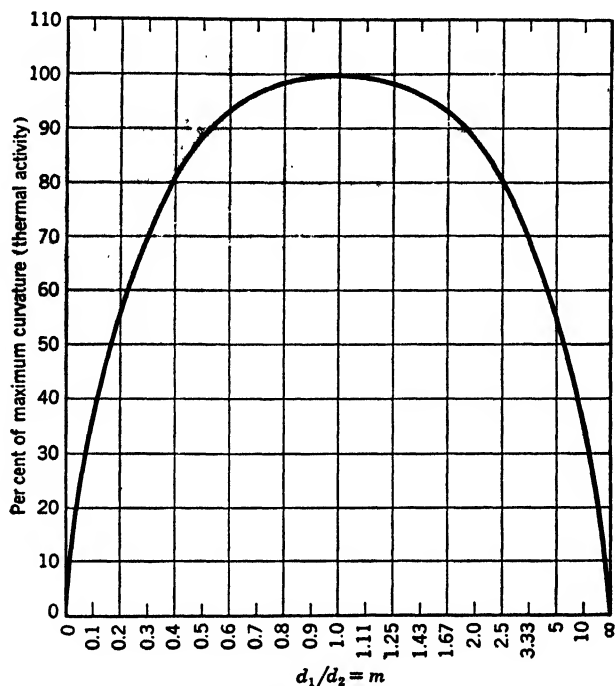


FIG. 7-6. Effect of Ratio of Thicknesses on Radius of Curvature of Strip.

The radius of curvature also is affected by the ratio of thicknesses:  $d_1/d_2 = 1$  being the best.

A discussion of these factors affecting thermostat strip bending or radius of curvature is illuminating. If the ratio of thicknesses of components is varied in either direction, these will vary as in Fig. 7-6, if the moduli of elasticity is assumed to be equal. It is interesting to note that the ratio can be widely varied, for instance, from 0.5 to 2.0 and still retain a high percentage, 88 per cent, of the maximum thermal activity.

The modulus of elasticity will be the same for both components only by coincidence. The effect of unequal moduli is illustrated in Fig. 7-7, it being assumed that the component thicknesses are equal. Figure 7-7

surprisingly shows that the ratio of moduli of the two components can vary from 0.3 to 3.3 and still show 91 per cent of the maximum thermal activity. Combinations having too great a difference in moduli as Invar-cadmium and Invar-hard rubber show no thermal activity whatsoever. Work that a thermostat metal element can do is proportional to the square of the difference of expansivities and proportional to the

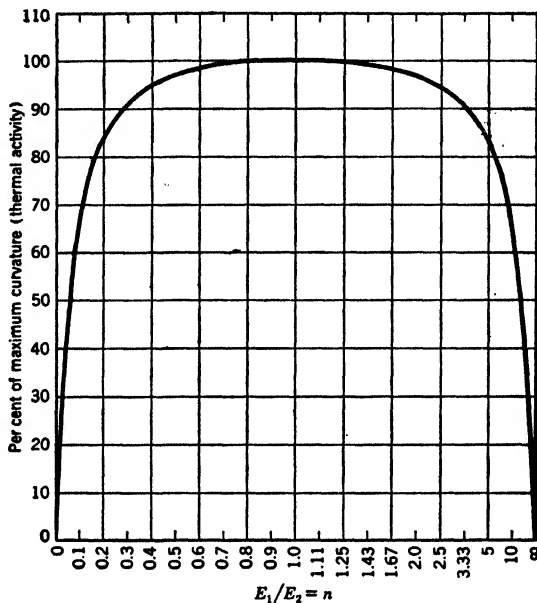


FIG. 7-7. Effect of Modulus of Elasticity on Radius of Curvature.

modulus of elasticity. The modulus of elasticity, or stiffness or rigidity, therefore is considered in the following. The general equation for stiffness or rigidity can be written as follows:

$$S = \frac{1}{3} (E_1 \alpha_1^3 + E_2 \alpha_2^3) - \frac{1}{4} \frac{(E_1 \alpha_1^2 - E_2 \alpha_2^2)^2}{(E_1 \alpha_1 + E_2 \alpha_2)} \quad (7-5)$$

where  $S$  = stiffness

The stiffness is therefore affected by the ratio of the moduli and also by the ratio of thicknesses of components. Analyzing the effect would be too lengthy for this article; therefore it is left out, but the conclusions of such an analysis are given in the following. To obtain the maximum work from a thermal element the thicknesses of the com-

ponents should be inversely proportional to the square roots of the moduli of elasticity. Figure 7-8 shows the optimum ratios of  $d_1/d_2$  and  $E_1/E_2$  and the percentage improvement in performance. With reference to Fig. 7-8, if the ratio of moduli  $n$  is 3.0, the optimum ratio of thickness  $m$  is 0.6, and the percentage improvement in performance is 16 per cent over a ratio of thicknesses of 1.0. Obviously, when  $n$  is

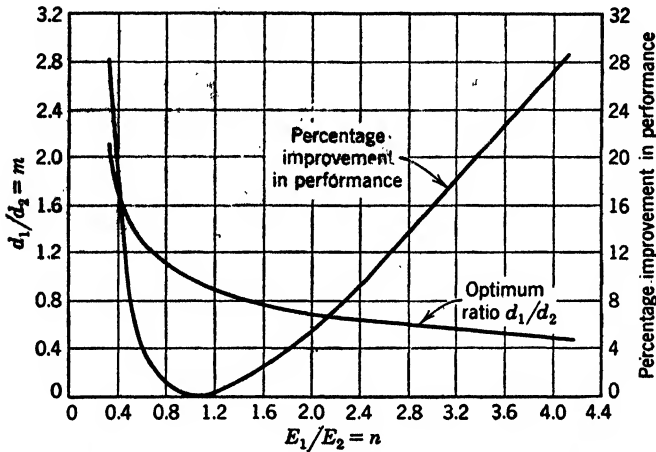


FIG. 7-8. Best Ratios of Thicknesses of Components to Obtain Maximum Output for Various Ratios of Moduli of Elasticity.

1.0,  $m$  also is 1.0. This is the optimum ratio, and no improvement in performance is possible by varying  $m$ .

### STRESSES

It is difficult to analyze properly the stresses in thermostat metal since there are so many factors which are difficult to evaluate. Stresses result from factors created during the functioning of a finished element (1) thermal changes, (2) mechanical loading, and factors originating from the manufacturing operations, (3) bonding, hot rolling, cold rolling, slitting, flattening, fabricating, and heat treating. The effect of (1) and (2) can be worked out fairly simply but (3) is almost impossible. Theoretical thermal and mechanical stresses are discussed in the following.

With reference to Fig. 7-4, the stress at the bond of a strip heated while free to move is

$$\text{Stress} = \frac{E}{2} (\alpha_2 - \alpha_1)(t_1 - t_0) \quad (7-6)$$

with the high-expansive component in compression and the low-expansive in tension. The outer fiber stresses for both components are one half of the bond stress with the high in tension and the low in compression. Zero stresses occur one sixth of the total thickness in from the outer surfaces. With reference to Fig. 7-3, the stresses resulting from uniformly heating and uniformly restraining the strip are

$$\text{Stress} = \frac{E}{2} (\alpha_2 - \alpha_1)(t_1 - t_0) \quad (7-7)$$

with the high-expansive component in compression and the low-expansive in tension, the stress being uniform throughout the thickness

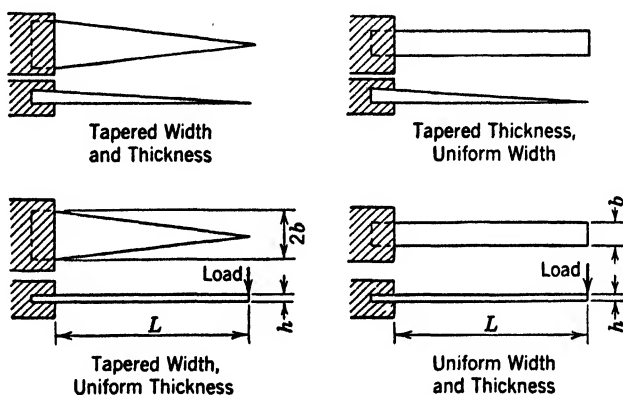


FIG. 7-9. Cantilever Elements of Various Designs.

of each. Note that these stresses are the same as the bond stresses of a free strip. If a straight cantilever strip of thermostat metal is heated with the free end unrestrained, the free end will move up as shown by the dotted lines in Fig. 7-5. If the free end is restrained in its original position and the strip heated, the stresses due to heating and the mechanical restraint will be maximum at or near the point of clamping (plane  $x-x$ , Fig. 7-5). The maximum stresses are at the outer fibers and are given by the following equation:

$$\text{Stress} = \frac{1}{8} E(\alpha_2 - \alpha_1)(t_1 - t_0) \quad (7-8)$$

The bond stresses, however, remain the same as the bond stresses in a free or uniformly restrained strip.

With reference to the cantilever strip previously mentioned, obviously this strip of uniform cross section is not efficient since only at the clamped end is it worked at full capacity. A tapered beam of uni-

form strength illustrated in Fig. 7-9 will give, for the same volume of thermostat metal, 33 per cent greater contact force and 43 per cent less stress. The thickness alone can also be tapered <sup>2</sup> as well as both width and thickness. These forms give better form economy than strip of uniform cross section, because of stressing the length uniformly. Lessening of the tendency to vibrate is another desirable feature of these strips tapered in both width and thickness.

Stresses due to mechanical loading can be calculated, if the element is considered not as laminated but as a single material, and usual formulas are employed. Stresses due to bonding, hot rolling, and the like are difficult to determine; therefore, after calculation of the simple thermal and mechanical stresses high safety factors must be used to arrive at allowable stresses.

The stress that a thermostat metal element can withstand without taking a permanent set (allowable stress) depends on the temperature and previous history such as the rolling, forming, and heat treatment. For most thermostat metals having for both components ferrous alloys, the following allowable working stresses can be used:

Temperature, °F	Allowable Working Stress, <i>f</i>
75	25,000
300	23,000
500	18,000
700	13,000
900	5,000
1,000	0-1,000

The following equation can be used to determine the allowable working loads for cantilever elements and helix- and spiral-coil elements:

$$P = \frac{fwt^2}{6L(\text{or } R)} \quad (7-9)$$

where *P* = allowable load, lb

*f* = allowable working stress, psi

*w* = width, in.

*t* = thickness, in.

*L* = length of cantilever, in.

*R* = radius arm of helix or spiral coil

The allowable stresses listed are approximate only and should be used with caution. As an illustration of the effect of previous history, experiments to determine allowable stresses on helix coils coiled in various ways (high-expanding component inside or outside) were made

by loading so as to unwind and also to wind the coils. Allowable stresses calculated from the data varied from 20,000 to 100,000 psi.

### ELECTRICAL RESISTIVITY

An increasing number of products are made, such as thermal relays, circuit breakers, and motor overload protectors, in which heat generated by passage of an electric current through a thermostat metal element operates the device. These applications require a variety of thermostat metals covering a wide range of electrical resistivities. A number were available for these applications several years ago, but the over-all variation in electrical resistivity was not sufficiently wide, and the resistivities were not properly spaced.

It is possible to make circuit breakers and similar equipment with widely different ratings using one type of thermostat metal by varying the size and shape of the element. But circuit-breaker manufacturers desired to make a line of circuit breakers all of the same physical size but varying in circuit interrupting power in uniform steps from low to high. The thermostat metal producers have designed a line of thermostat metals to fill this need.

The heating effect of an electric current is

$$H = \frac{ri^2t}{4.18} \quad (7-10)$$

where  $H$  = calories

$r$  = resistance, ohms

$i$  = amperes

$t$  = time, sec

The temperature rise (disregarding heat losses) of a resistor is given by

$$\Delta T = \frac{0.43ri^2t}{MS} \quad (7-11)$$

where  $\Delta T$  = temperature rise, °F

$M$  = mass, grams

$S$  = specific heat

The heating effect is proportional to  $i^2r$  in which  $i^2$  is analogous to the current rating of a breaker and  $r$  is analogous to the electrical resistivity of the thermostat metal. Throughout a line of circuit breakers, the heating effect which is proportional to  $i^2r$  must be a constant for uniform tripping time. Therefore, the series of thermostat metals must vary in electrical resistivity as the square of the rating. The fol-

lowing equation is useful in laying out a line of breakers since, after the type of material has been experimentally determined for one rating, the others can be approximately calculated.

$$I^2R = \text{constant}$$

$I$  = current rating of breaker

$R$  = resistivity of thermostat metal

The equation is useful also in determining whether the design of the line of breakers is such as to make best use of the range of resistivity materials available. The highest rating should use the lowest resistivity material or the lowest rating the highest resistivity material.

The range of electrical resistivities available before the advent of special electrical-resistivity series is illustrated by the thermostat metals listed in Table 7-1. Thermostat metals are not yet standardized, and, therefore, the types mentioned in the table and later in this chapter are types manufactured by the General Plate Division, Metals & Controls Corporation, Attleboro, Mass.

TABLE 7-1

Thermostat Metal	Electrical Resistivity at 75°F, ohms per circular-mil-ft
A1	90
N1	95
E5	345
E1	500

The special thermostat metals developed to meet the requirements set forth above were based on standard thermostat metals such as type E1 in Table 7-1. The resistivity was varied by incorporating a third layer of variable thickness of a relatively low-resistivity metal. This filled in the range from 125 to 470 ohms per circular-mil-foot. A series from 20 to 100 ohms per circular-mil-foot utilized high-conductivity copper alloys for the third layer. The resistivity can be calculated easily if the three laminations are considered as a parallel circuit:

$$\frac{x}{r_1} + \frac{y}{r_2} + \frac{z}{r_3} = \frac{100}{R} \quad (7-12)$$

where  $x$ ,  $y$ , and  $z$  = thicknesses of components  $x$ ,  $y$ , and  $z$  in per cent of the total thickness of the three

$r_1$ ,  $r_2$ , and  $r_3$  = resistivities of the three components

$R$  = resistivity in ohms per circular-mil-foot of the combination



The recent introduction of a high-manganese alloy of 1050 ohms per circular-mil-foot as a thermostat metal component has increased the top limit to 850 ohms per circular-mil-foot. Electrical resistivities above 500 ohms per circular-mil-foot have been obtained using nickel-

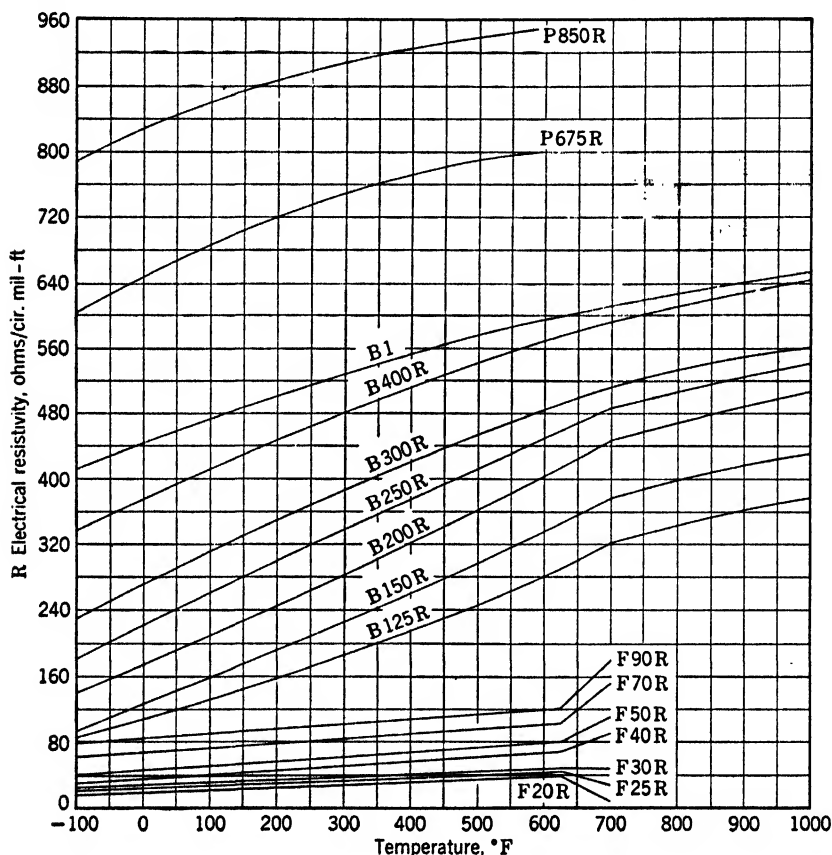


FIG. 7-10. Electrical Resistivity versus Temperature Curves of a Group of Thermostat Metals Designed for Use in Circuit Breakers and Electric Overload Devices.

chromium resistance alloys as well as nickel-chromium-aluminum-iron and nickel-manganese-aluminum-iron alloys.

Figure 7-10 gives the resistivity versus temperature curves of a series of electrical-resistivity thermostat metals whose resistivities at 75°F cover the range from 20 to 850 ohms per circular-mil-foot. The resistance versus temperature information is important in design work for obvious reasons. The resistance at the operating temperature and

the rate of increase with temperature rise (coefficient of resistance) is equal in importance to that at room temperature.

### CHOICE OF ALLOYS

In choosing components to use in thermostat metals numerous factors must be kept in mind to produce an efficient, economical, and accurate finished product. First, since the rate of thermal activity is propor-

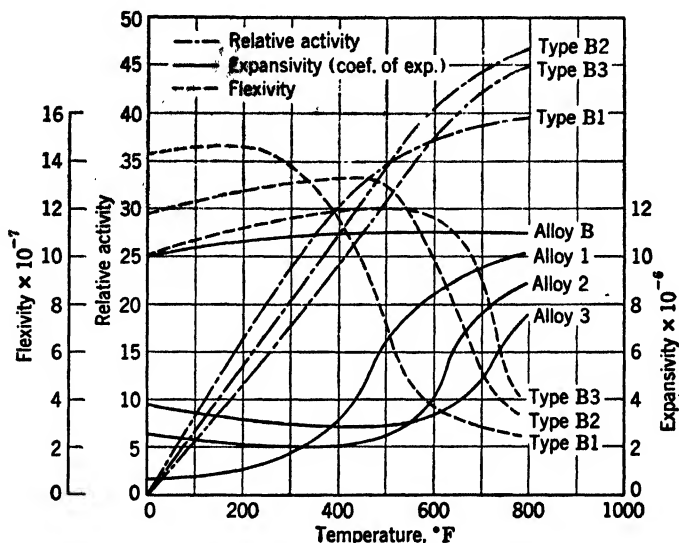


FIG. 7-11. Curves Illustrating Relation among Expansivities (Coefficients of Expansion), Relative Activities, and Flexivities of High and Low Expansivity Alloys and Thermostat Metals Composed of Them.

tional to difference in expansivities of the two components (see equation 7-1) materials must be chosen to have as low and as high expansivities as possible. Also the rate of change of the expansivities must be such to give the required linearity or required deviation from linearity of thermal activity over the required operating range. Usually constancy of expansivities is desirable although for special applications varying expansivities are used to give desirable activity rate. Some types of characteristic activity curves are as follows: (1) Relatively low activity until a predetermined temperature is reached, (2) accelerating activity, (3) decelerating activity, (4) decelerating activity above a predetermined temperature, (5) no activity above a predetermined temperature, and (6) reversed activity above a

predetermined temperature. Depending on the temperature range encompassed, several of the types mentioned may occur in the characteristic activity curve of one thermostat metal. High or low expansivities are useless if the expansivity is not reversible, since the resulting hysteresis would destroy the reproducibility and reliability of operation. Therefore, either elemental metals or solid-solution alloys are preferred to those containing compounds, exhibiting phase changes, or changing solubility of one constituent with temperature.

The ability to do work is related to the modulus of elasticity as previously mentioned and, therefore high modulus materials are preferred. Materials with high strengths, proportional limits, and creep strengths are needed to withstand the high thermal and mechanical stresses created in elements at high temperature and when heavily loaded.

For low-expansive components alloys of the Invar group (nickel-iron alloys) are generally chosen. The expansivities versus temperature curves of a group are shown in Fig. 7-11. Salient features as the nickel content increases above 36 per cent are as follows:

1. The inflection temperature increases.
2. The temperature at which the minimum expansivity occurs increases.
3. The temperature range corresponding to a relatively low expansivity increases.

Therefore, when these nickel-iron alloys are laminated to a given high-expansive component with an expansivity which does not vary significantly with temperature, increase in the nickel content:

1. Raises the temperature at which maximum activity occurs.
2. Decreases the magnitude of the maximum activity.
3. Increases the temperature range of relatively uniform activity.

These effects are shown in Fig. 7-11. This chart gives considerable information. As already noted, the expansivity versus temperature curves for three nickel-iron alloys (increasing in nickel content from 1 to 3) are given as well as that for an alloy having a high expansivity. The flexivities of the three types of thermostat metals composed of the alloy with the high expansivity bonded to the three alloys having low expansivities, respectively, are given. Flexivity, a fundamental activity constant, is defined in the section on Standard Test and Purchase Specifications, page 370. These calculated flexivities come surprisingly close to the flexivities obtained from actual activity data, as may be seen by comparing these flexivity curves with curves on Fig. 7-17. The

relative activity curves of the three types of thermostat metals are included in the chart. These are the characteristic activity curves of movement versus temperature in inches or angular degrees, or the like, depending on the form of element.

The flexivity curve is the curve of the first derivative of the relative activity curve. Any point on the flexivity curve denotes the slope of the corresponding point on the relative activity curve. The calculation

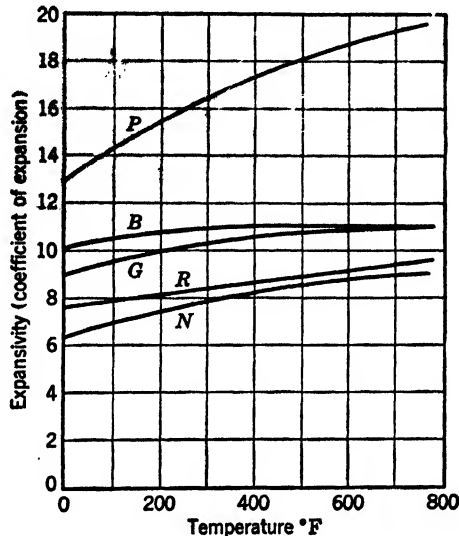


FIG. 7-12. Expansivities (Coefficients of Expansion) of a Few High-Expansivity Alloys.

of the flexivity from the expansivity data is relatively simple, since from the general equation of the curvature of thermostat metal strip the following relation can be derived:

$$\text{Flexivity, } F = \frac{3}{2}(\alpha_2 - \alpha_1) \quad (7-13)$$

The Invar-type low-expansive alloys in some cases have been modified by the addition of chromium, molybdenum, and cobalt for high-temperature strength and scaling resistance.

High-expansive components are of a greater variety than low. Brass was one of the original ones and is still used because of its high expansivity. Disadvantages are its low maximum temperature of use, 300 to 350°F and the difficulty of processing the soft brass in combination with hard Invar. Monel was an improvement followed by aus-

tenitic nickel-chromium-iron and nickel-manganese-iron alloys. Pure nickel and nickel-molybdenum-iron alloys also are used.

The introduction of the high-manganese nickel-copper alloys about 1941 was the most significant advance in high-expansion alloys since the advent of thermostat metals. These alloys have approximately 50 per cent greater expansivity than previously used alloys. In addition to high expansivity they have very high electrical resistivity, as mentioned on page 362 in the section on electrical resistivity. The expansivity versus temperature curves of some high-expansivity alloys are given in Fig. 7-12.

### HEAT TREATMENT

As mentioned in the section on stresses, stresses of unknown magnitude due to cold rolling, roller flattening, slitting, piercing, forming, and so on are present in an element. If assembled into a thermostat or other thermally operated device, relief of these stresses and subsequent permanent deformation and upsetting of calibration may take place. Stress relief or more correctly stress redistribution is obtained by appropriate heat treatment. The heat treatment will relieve the mechanical stresses of fabrication, and, also, the thermal stresses produced by heat treatment will cause yielding in highly stressed points, and this yielding produces a redistribution of the stresses in such manner as to withstand normal operating stresses due to temperature and loading. The temperature of heat treatment should be approximately 100°F over the maximum temperature met with in use. Any forming or permanent mechanical change in a heat-treated element should be followed by another heat treatment. If the element is to be used for low-temperature work, subjecting it to lower temperatures than those met with in use imparts stability. Cycling several times from high to low temperature is efficient in stabilizing an element quickly.

In ordinary high-temperature thermostat metals, thermal activity constants decrease with increase of heat-treating temperature up to approximately 700-900°F and then increase again. The increase may be due to incipient recrystallization (annealing). The usual heat treatment does not affect the structure of the component alloys in any way or soften or harden them. Elements which in service are under restraint can be materially improved in resistance to permanent set by heat treating under similar restraint. The element must in service be subjected to restraint only in the same direction since restrained heat treating decreases the resistance to stresses opposite to those developed by the treatment.

### HARDNESS

Since thermostat metals are composed of elemental metals or solid-solution alloys, hardness is obtained only by cold rolling. This cold rolling determines the hardness and elastic properties. High hardnesses usually indicate high elastic properties; therefore, high degree of hardness is desirable unless severe forming operations or sharp bends require a softer material. The elastic properties can be conveniently evaluated by the hardness, and hardness tests are routine in quality control. Most thermostat metal is used in relatively thin strip in which one component is usually one-half the total thickness. Therefore, hardness test methods are limited to those having very light loads and depths of penetration such as Vickers, Eberbach, Microhardness, Tukon, or Knoop. Even with these instruments hardness of strip having thicknesses of the order of 0.001 to 0.003 in. is difficult to determine accurately.

### SURFACE CONDITION

As in any high-quality metal article the surface should be as free from defects and imperfections as possible. However, since thermostat elements operate by changes in temperature, the surface should be as receptive to absorption of heat or radiation of heat as possible. This calls for a dull matte finish rather than a bright polished finish. In most applications, rate of absorption or radiation of heat is not too critical, and normal cold-rolled finishes are used. The thinner the strip, the more important is the surface for its performance, since very thin strip consists essentially of two surfaces with very little material between. Surfaces approaching perfection are desired in this instance.

If a matte or black finish is desired it can be developed chemically or mechanically. One chemical process is to electroplate with copper and then oxidize by heat treatment or reaction with sulfides. A recently developed process of producing an adherent thin black surface finish on high-alloy ferrous alloys, consisting of heating in a molten sodium or potassium dichromate bath at 650–750°F, lends itself admirably to thermostat metal since the surface conditioning and heat treatment can be combined into one operation. This process is said to increase corrosion resistance. Fine abrasive blasting processes (Vapor blast, Microblast) are mechanical means of producing a matte finish. The finest meshes of abrasive should be used so that only the outer surface skin is affected. The detrimental effect of a coarse rough surface is illustrated by a 15 per cent decrease in thermal activity ob-

served on a 0.020-in.-thick element blasted with 16-mesh metallic grit. Carburizing, nitriding, calorizing, and other treatments that chemically affect the surface should be avoided.

#### CORROSION RESISTANCE AND PROTECTION

Although most alloys used in thermostat metals are inherently corrosion-resistant, when combined in a thermostat metal galvanic couples may be produced. In corrosive media such as water and steam, careful choice of type of thermostat metal must be made to prevent rapid and disastrous failures. Brass-Invar and silicon-bronze-Invar combinations in some hard waters may disintegrate sufficiently in a few weeks to become inoperative. Combinations must be chosen in which the components individually are corrosion-resistant and which in combination do not produce a destructive galvanic couple. Unfortunately, such combinations are rare between high- and low-expansive components, and the few good combinations from the corrosion standpoint have low thermal activities. One good type listed further in the group on which detailed data are given has been in use in various water-mixing valves for over 8 years, without a reported failure due to corrosion.

Of course, the mounting brackets and the like must be of material which will not react with the thermostat element. Tin and lead coatings by dipping are used in some thermostat metal elements with good results. Zinc, cadmium, nickel, and chromium electroplating is also common practice to protect the surface with usually, however, indifferent results.

#### THERMAL CONDUCTIVITY

The rate of transfer of heat from its surface into the body of a thermostat element is dependent on its thermal conductivity. Therefore, the thermal conductivity may be, depending on the application, of considerable importance.

Heat can be transferred to an element by radiation, convection, or conduction. The heat thus transferred is absorbed into the body of the element by conduction. Heat supplied by a heater near the element is an example of the first, and heat supplied by circulating air is an example of the second way. Since in most cases thermostat metal elements are made of relatively thin strips or sheets, the surface condition is more important for heat transfer by convection and radiation than the thermal conductivity. This follows because the mass is small compared to the surface area.

In numerous applications, such as iron thermostats, aquastats, and fluorescent starters, heat transfer to the element is mainly by conduction through the mounting bracket. In these cases the thermal conductivity is of importance.

The thermal conductivities of most metals and alloys are roughly proportional to their electrical conductivities. This fact can be used to get a rough approximation of the thermal conductivity:

$$\begin{aligned} &\text{Thermal conductivity, calories per second per square centimeter per degree Centigrade per centimeter} \\ &= 12/\text{electrical resistivity, ohms per circular-mil-foot} \quad (7-14) \end{aligned}$$

Thermostat metals are made up of two or more components which may differ in thermal conductivity greatly. Naturally, the longitudinal passage of heat parallel to the laminas is not the same as that perpendicular to them. If one knows the thermal conductivities of the components, it is simple to calculate the longitudinal and/or perpendicular conductivity of the whole. The flow of heat parallel or perpendicular to the laminas follows the same laws as flow of electricity through parallel and series resistances. The thermal conductivity can be changed to thermal resistance (the reciprocal), and thus formulas analogous to electrical-resistance formulas can be used.

### SPECIFIC HEAT

The specific heat determines the amount of heat energy necessary to raise the temperature of a thermostat metal element any given amount. Usually the amount of heat available is so great that this factor is not too important except possibly in the case of the heating by passage of electric current (see page 360). There is, however, little choice among the various thermostat metals available, since all their specific heats are very close to 0.12 Cal per gram per degree centigrade (the value is the same for British thermal units per pound per degree Fahrenheit).

### STANDARD TEST AND PURCHASE SPECIFICATIONS

The properties and attributes that affect performance of thermostat metal are logical items that are covered by specifications. These include chemical analysis, quality of bond, quality of surface, thickness, width, length, cross, lengthwise and edgewise curvatures, hardness, thermal activity, electrical resistivity, temperature coefficient of electrical resistivity, stiffness or torque, and marking or identification of type and/or high- or low-component side.



Thermal activity being the most important has in the past been specified in a large variety of ways using numerous test specimen sizes and shapes. The American Society for Testing Materials has developed method B106-40 for flexivity, which is a great improvement over previous methods since it gives a fundamental value of activity independent of size or shape. Flexivity is defined as "the change of curva-

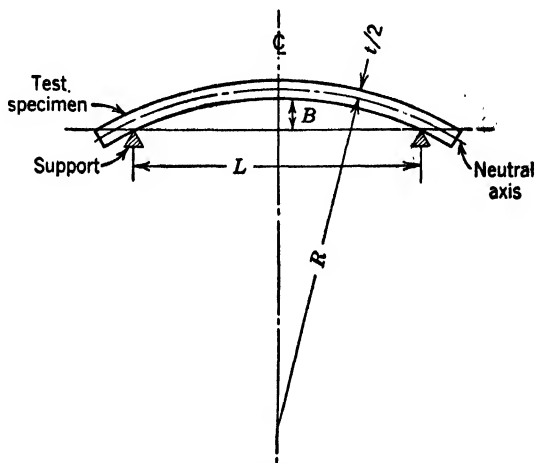


FIG. 7-13. Schematic Diagram of Test for Flexivity.

ture of the longitudinal center line of the specimen per unit temperature change for unit thickness" and is given by the following formula (see Fig. 7-13):

$$F = \frac{\left( \frac{1}{R_2} - \frac{1}{R_1} \right) t}{T_2 - T_1} \quad (7-15)$$

where

$$\frac{1}{R} = \frac{8B}{L^2 + 4Bt + 4B^2} \quad (7-16)$$

$F$  = flexivity

$R_2$  and  $R_1$  = radii of curvature, in.

$T_2$  and  $T_1$  = temperature, °F

$t$  = thickness, in.

$B$  = movement, in.

Other ASTM test methods are as follows:

1. Standard Method of Test for Resistivity of Metallic Materials, B63-36.
2. Standard Method of Test for Change of Resistance with Temperature of Metallic Materials for Electric Heating, B70-39.
3. Tentative Method of Test for Equivalent Yield Stress of Thermostat Metals, B191-44.

Other important properties such as hardness, elastic properties, and modulus of elasticity are being developed.

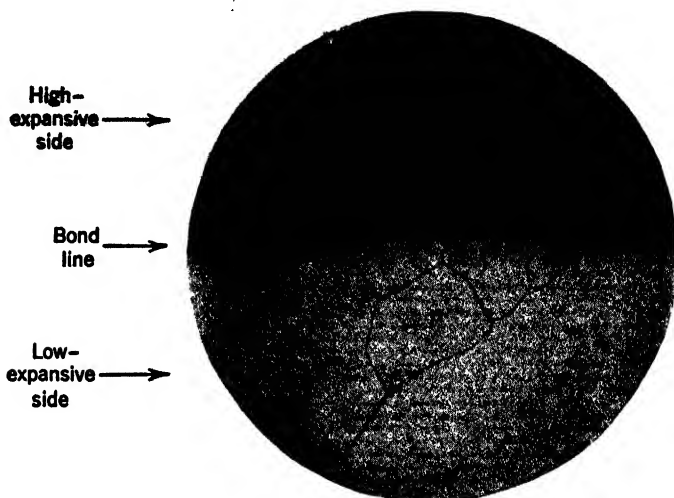


FIG. 7-14. Cross Section of Bond. Note that grain structure is continuous through bond line. Magnification—about 350 $\times$ .

Thermostat metals in the trade are classified into two main groups: low-temperature and high-temperature thermostat metals. This classification, unfortunately, has little to do with the temperature range of uniform or linear activity but only defines the types as to maximum temperatures to which they can be subjected without damage. Brass-Invar and silicon-bronze-Invar, and nickel-iron-chromium-alloy-Invar thermostat metals are examples of low- and high-temperature types with maximum temperatures of use of 350 to 600°F and 1000°F, respectively. Usually low-temperature types have for their high-expansion components nonferrous copper-base alloys. The high-temperature types are mainly composed of components both of which are ferrous alloys.

Thermostat metals as yet are not standardized, and, therefore, each producer has his own proprietary designation for each type.

### BOND

Three main processes are used to create the bond between components:

1. Casting the lower-melting alloy on the solid higher-melting one.
2. Soldering or brazing the components together.
3. Welding the components directly together by heat and/or pressure in the solid state without an intermediate soldering or brazing layer.

Method 1 can be used only where the melting points differ considerably and is limited to the low-temperature metals such as brass-Invar.

Method 2 avoids the drawbacks of method 1 but, owing to the brazing or soldering material usually being weaker than either component, introduces a weak zone exactly in the place where maximum thermal stress occurs.

Method 3 avoids the drawbacks of both methods 1 and 2 and is the most widely used method for high-quality high-temperature metals. The completeness of the weld made by this method is shown by Fig. 7-14.

### TYPES OF ELEMENTS

The varieties of thermostat-metal element shapes possible are almost without number, but they can be classified into the following general group shapes:

1. Straight strips—the fundamental form. Straight strips can be used as cantilever beams (clamped at one end, other end free) or as simple beams (supported at both ends but ends not clamped since this would restrict movement).
2. U shapes. A U shape is an element which is a combination of a half circle and two straight strips.
3. Spiral coils—sometimes called clock-spring-type coils.
4. Helix coils.
5. Double helix coils.

These five shapes are illustrated in Fig. 7-15A. Many shapes are possible by combining these shapes or portions of them (Fig. 7-15B, C).

### FORMULAS

Formulas have been developed relating the dimensions, temperature change, and activity and torque or force constants of the various shapes of elements, and these are listed in Table 7-2. These formulas are all

TABLE 7-2. SUMMARY OF FORMULAS

	Deflection	Force	Force-Temperature	
Cantilever	$B = \frac{c_2(T_2 - T_1)L^2}{t}$	$P = \frac{a_2Bwt^3}{L^3}$	$P = \frac{b_2(T_2 - T_1)wt^3}{L}$	(7-17)
Simple beam	$B = \frac{c_2(T_2 - T_1)L^2}{4t}$	$P = \frac{16a_2Bwt^3}{L^3}$	$P = \frac{4b_2(T_2 - T_1)wt^3}{L}$	(7-18)
U shape (for small radius at bend)	$B = \frac{c_2(T_2 - T_1)L^2}{2t}$	$P = \frac{4a_2Bwt^3}{L^3}$	$P = \frac{2b_2(T_2 - T_1)wt^3}{L}$	(7-19)
Spiral and helix	$A = \frac{c_1(T_2 - T_1)L}{t}$	$P = \frac{a_1Awt^3}{Lr}$	$P = \frac{b_1(T_2 - T_1)wt^3}{r}$	(7-20)
Double helix	$B = \frac{c_3(T_2 - T_1)LD}{t}$	$P = \frac{a_3Bwt^3}{LD^2}$	$P = \frac{b_3(T_2 - T_1)wt^3}{D}$	(7-21)
Flexivity	$F = \frac{\left(\frac{1}{R_2} - \frac{1}{R_1}\right)t}{T_2 - T_1}$	(See also formula (7-15))		(7-22)
where $\frac{1}{R} = \frac{8B}{L^2 + 4Bt + 4B^2}$	(See also formula (7-16))			(7-23)

## GENERAL LAWS GOVERNING THERMOSTAT METALS

Deflection on temperature change varies:

For Cantilever, Simple Beam,  
and U Shape

For Spiral and Helix

For Double Helix

Directly as temperature change  
Directly as length squared  
Inversely as thicknessDirectly as temperature change  
Directly as length  
Inversely as thicknessDirectly as temperature change  
Directly as length  
Directly as diameter  
Inversely as thickness

Force exerted on temperature change varies:

For Cantilever, U Shape, and  
Simple Beam

For Spiral and Helix

For Double Helix

Directly as temperature change  
Directly as width  
Directly as thickness squared  
Inversely as lengthDirectly as temperature change  
Directly as width  
Directly as thickness squared  
Inversely as radiusDirectly as temperature change  
Directly as width  
Directly as thickness squared  
Inversely as diameter $t$  = thickness, in. $w$  = width, in. $L$  = active length of strip, in. $a_1$  = torque constant, coils $a_2$  = force constant, strip, U shape $a_3$  = force constant, double helix coil $b_1$  = torque-temperature constant, coils $b_2$  = force-temperature constant, strip, U shape $b_3$  = force-temperature constant, double helix coils $c_1$  = thermal-activity constant, coils $c_2$  = thermal-activity constant, strip, U shape $c_3$  = thermal-activity constant, double helix coils $B$  = deflection, strip, in. $A$  = angular rotation, coils, degrees $P$  = force, lb $r$  = radius (at point load is applied), in. $T_2 - T_1$  = temperature change, °F $F$  = flexivity $R$  = radius of curvature

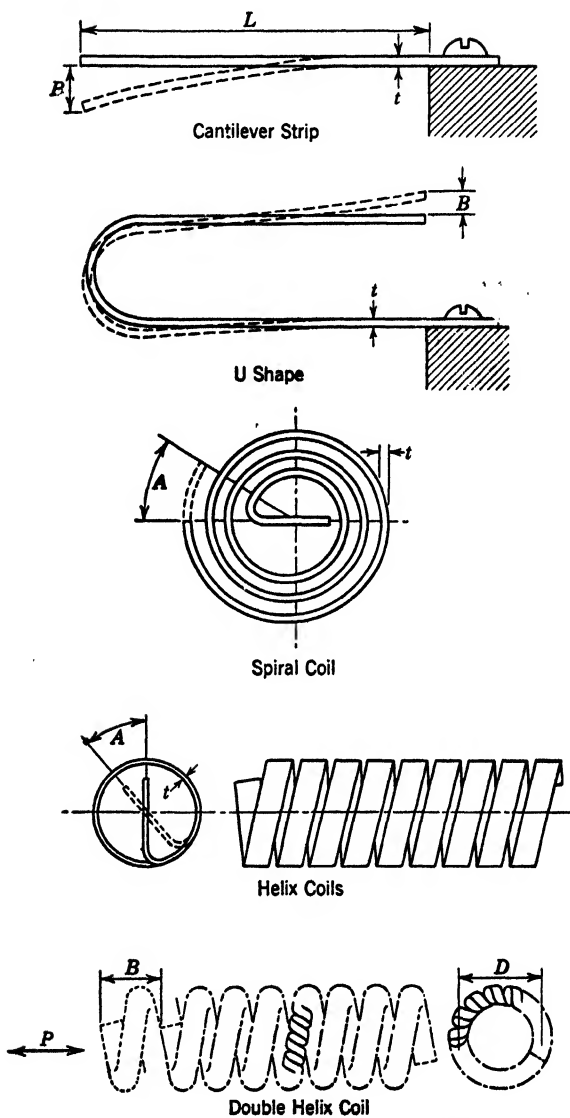


FIG. 7-15A. Fundamental Types of Thermostat Metal Elements.

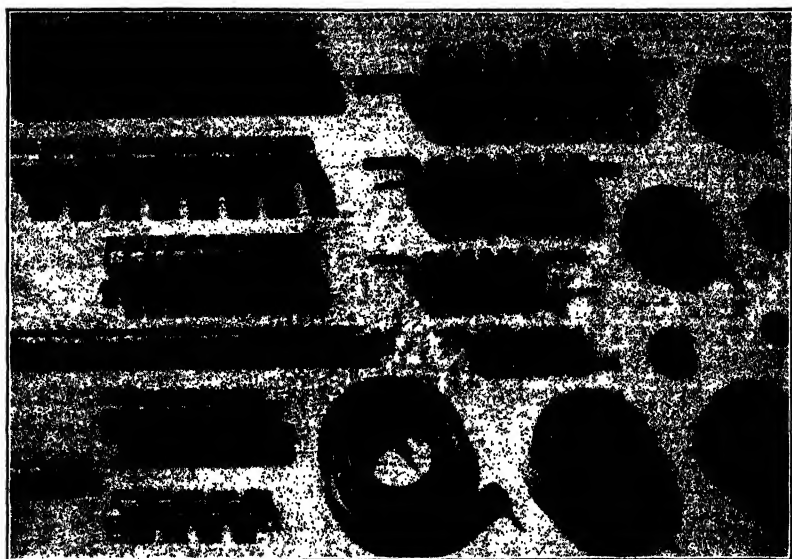


FIG. 7-15B. Typical Helix and Spiral Coils.

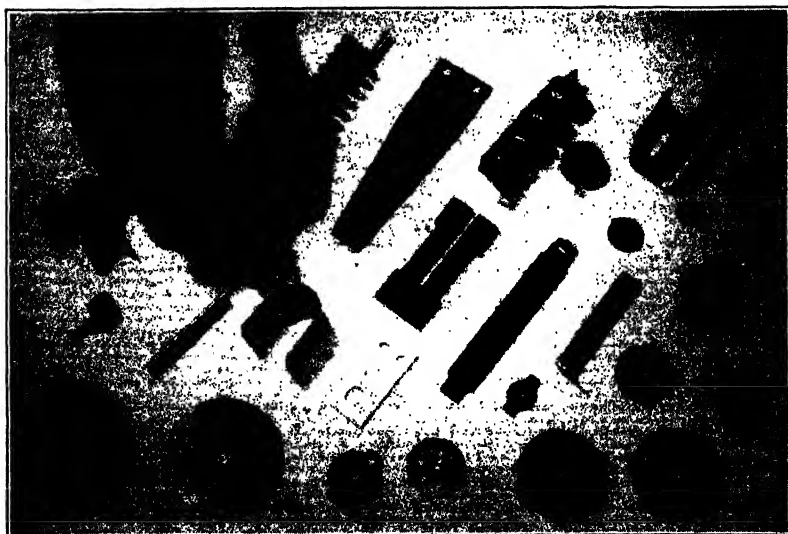


FIG. 7-15C. Variety of Thermostat Metal Elements in Common Use.

directly developed from the general equation of thermal bending (equation 7-1) and from standard deflection-load formulas. These are, of course, simplified equations where insignificant terms have been dropped, and, where several constants are involved, they have been combined into one. Although not theoretically exact, they are useful in general work calculating various types of elements for specific uses.

#### APPLICATION OR USE

In designing a thermostat element into a thermometer, thermostat, or other thermally operated device, the problem is one of choosing the most economical type of material and shape of element to produce the required movement and/or force. The type having the highest thermal activity in the working temperature range is usually chosen, although this is not always true. If a wide range of calibration or adjustment in a small space is required, a low-thermal-activity material may be optimum. Also where the length of element and movement for a given temperature range are specified, a thin low-thermal-activity material element can be used to advantage. An element of high thermal activity may require increased thickness to bring down the movement to that specified. Besides the thermal activity, other factors such as corrosion resistance, thermal conductivity, and electrical resistivity influence the choice.

After choice of type of material, shape of element is chosen that will move thermally in the correct way to perform the required cycle of operation and that will fit into the available space. The straight strip gives essentially linear movement for small temperature changes. The U shape similarly gives linear motion with a more compact design. The coils, spiral and helix, give rotating motion, which is uniquely adapted to thermometers and other dial-type devices. The spiral coil is also the most compact type of element.

The double helix coil has the special property of expanding or contracting (depending on the way of coiling—primary-helix-coiled high-expansive component inside or outside, primary-helix-coiled left- or right-hand and secondary-helix-coiled left- or right-hand) with temperature rise. If a slight angular rotation is disregarded, the movement is true linear movement. Another feature is the small cross-sectional area and long length of the strip making up the coil. This gives a relatively high electrical resistance and high thermal-energy release on passage of electric current.

TABLE 7-3

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Remarks
Time $\times 10^3$	$\times 10^{-1}$	$\times 10^{-2}$	$\times 10^{-3}$	$\times 10^{-4}$	$\times 10^{-5}$	$\times 10^{-6}$	$\times 10^{-7}$	$\times 10^{-8}$	$\times 10^{-9}$	$\times 10^{-10}$	$\times 10^{-11}$	$\times 10^{-12}$	$\times 10^{-13}$	$\times 10^{-14}$	$\times 10^{-15}$	H.S. L.S.			
Brass-Invar	156	105	83	74	67	61	56	51	47	43	40	37	34	31	28	25	22	20	
Al	145	97	75	68	64	59	54	50	46	42	39	36	33	30	27	24	21	19	
Fe	124	86	65	58	55	50	46	42	39	36	33	30	27	24	21	19	17	15	
Si	108	72	51	45	42	38	35	32	29	26	23	20	18	16	14	12	10	9	
Be	135	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Bi	100	67	48	41	37	33	30	27	24	21	19	17	15	13	11	9	8	7	
Sn	80	53	36	30	27	24	21	19	17	15	13	11	9	8	7	6	5	4	
Ag	60	40	31	27	24	21	19	17	15	13	11	9	8	7	6	5	4	3	
Cu	139	95	74	65	60	55	50	46	42	39	36	33	30	27	24	21	19	17	
G	112	76	59	52	48	44	40	36	33	30	27	24	21	19	17	15	13	11	
Co	106	71	50	43	40	36	33	30	27	24	21	19	17	15	13	11	10	9	
Cr	82	41	33	28	25	22	20	18	16	14	12	10	9	8	7	6	5	4	
Fe	135	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Al	150	100	80	71	64	59	54	50	46	42	39	36	33	30	27	24	21	19	
Si	112	75	59	52	48	44	40	36	33	30	27	24	21	19	17	15	13	11	
Be	103	69	54	48	45	41	37	33	30	27	24	21	19	17	15	13	11	10	
Sn	78	52	41	36	33	30	27	24	21	19	17	15	13	11	9	8	7	6	
Ag	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Cu	124	80	61	53	49	45	41	38	35	32	29	26	23	20	18	16	14	12	
Fe	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Al	150	100	80	71	64	59	54	50	46	42	39	36	33	30	27	24	21	19	
Si	112	75	59	52	48	44	40	36	33	30	27	24	21	19	17	15	13	11	
Be	103	69	54	48	45	41	37	33	30	27	24	21	19	17	15	13	11	10	
Sn	78	52	41	36	33	30	27	24	21	19	17	15	13	11	9	8	7	6	
Ag	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Cu	124	80	61	53	49	45	41	38	35	32	29	26	23	20	18	16	14	12	
Fe	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Al	150	100	80	71	64	59	54	50	46	42	39	36	33	30	27	24	21	19	
Si	112	75	59	52	48	44	40	36	33	30	27	24	21	19	17	15	13	11	
Be	103	69	54	48	45	41	37	33	30	27	24	21	19	17	15	13	11	10	
Sn	78	52	41	36	33	30	27	24	21	19	17	15	13	11	9	8	7	6	
Ag	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Cu	124	80	61	53	49	45	41	38	35	32	29	26	23	20	18	16	14	12	
Fe	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Al	150	100	80	71	64	59	54	50	46	42	39	36	33	30	27	24	21	19	
Si	112	75	59	52	48	44	40	36	33	30	27	24	21	19	17	15	13	11	
Be	103	69	54	48	45	41	37	33	30	27	24	21	19	17	15	13	11	10	
Sn	78	52	41	36	33	30	27	24	21	19	17	15	13	11	9	8	7	6	
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Cu	124	80	61	53	49	45	41	38	35	32	29	26	23	20	18	16	14	12	
Fe	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Al	150	100	80	71	64	59	54	50	46	42	39	36	33	30	27	24	21	19	
Si	112	75	59	52	48	44	40	36	33	30	27	24	21	19	17	15	13	11	
Be	103	69	54	48	45	41	37	33	30	27	24	21	19	17	15	13	11	10	
Sn	78	52	41	36	33	30	27	24	21	19	17	15	13	11	9	8	7	6	
Ag	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Cu	124	80	61	53	49	45	41	38	35	32	29	26	23	20	18	16	14	12	
Fe	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Al	150	100	80	71	64	59	54	50	46	42	39	36	33	30	27	24	21	19	
Si	112	75	59	52	48	44	40	36	33	30	27	24	21	19	17	15	13	11	
Be	103	69	54	48	45	41	37	33	30	27	24	21	19	17	15	13	11	10	
Sn	78	52	41	36	33	30	27	24	21	19	17	15	13	11	9	8	7	6	
Ag	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Cu	124	80	61	53	49	45	41	38	35	32	29	26	23	20	18	16	14	12	
Fe	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Al	150	100	80	71	64	59	54	50	46	42	39	36	33	30	27	24	21	19	
Si	112	75	59	52	48	44	40	36	33	30	27	24	21	19	17	15	13	11	
Be	103	69	54	48	45	41	37	33	30	27	24	21	19	17	15	13	11	10	
Sn	78	52	41	36	33	30	27	24	21	19	17	15	13	11	9	8	7	6	
Ag	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Cu	124	80	61	53	49	45	41	38	35	32	29	26	23	20	18	16	14	12	
Fe	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Al	150	100	80	71	64	59	54	50	46	42	39	36	33	30	27	24	21	19	
Si	112	75	59	52	48	44	40	36	33	30	27	24	21	19	17	15	13	11	
Be	103	69	54	48	45	41	37	33	30	27	24	21	19	17	15	13	11	10	
Sn	78	52	41	36	33	30	27	24	21	19	17	15	13	11	9	8	7	6	
Ag	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Cu	124	80	61	53	49	45	41	38	35	32	29	26	23	20	18	16	14	12	
Fe	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Al	150	100	80	71	64	59	54	50	46	42	39	36	33	30	27	24	21	19	
Si	112	75	59	52	48	44	40	36	33	30	27	24	21	19	17	15	13	11	
Be	103	69	54	48	45	41	37	33	30	27	24	21	19	17	15	13	11	10	
Sn	78	52	41	36	33	30	27	24	21	19	17	15	13	11	9	8	7	6	
Ag	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Cu	124	80	61	53	49	45	41	38	35	32	29	26	23	20	18	16	14	12	
Fe	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Al	150	100	80	71	64	59	54	50	46	42	39	36	33	30	27	24	21	19	
Si	112	75	59	52	48	44	40	36	33	30	27	24	21	19	17	15	13	11	
Be	103	69	54	48	45	41	37	33	30	27	24	21	19	17	15	13	11	10	
Sn	78	52	41	36	33	30	27	24	21	19	17	15	13	11	9	8	7	6	
Ag	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Cu	124	80	61	53	49	45	41	38	35	32	29	26	23	20	18	16	14	12	
Fe	134	90	71	62	58	53	49	45	41	38	35	32	29	26	23	20	18	16	
Al	150	100	80	71	64	59	54	50	46	42	39	36	33	30	27	24	21	19	
Si	112	75	59	52	48	44	40	36	33	30	27	24	21	19	17	15	13	11	
Be	103	69	54	48	45	41	37</												



## PHYSICAL CONSTANTS

In Table 7-3 is listed a large group of thermostat metals and their physical constants. These include all the constants that apply to the

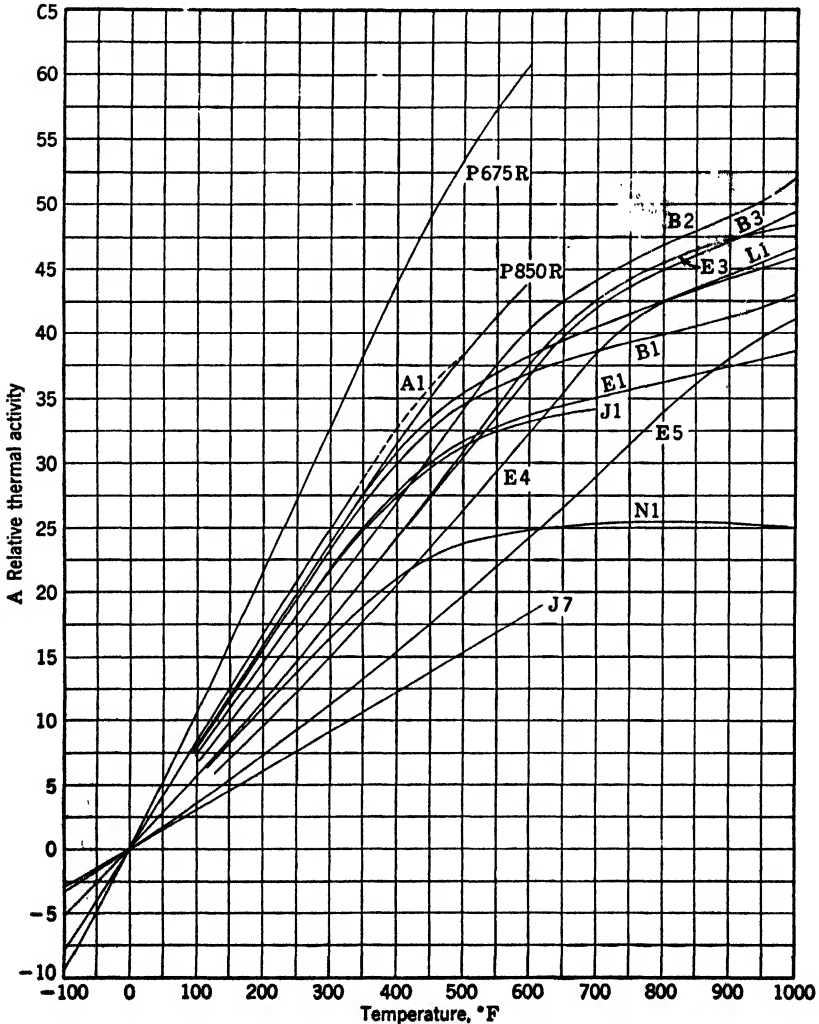


Fig. 7-16. Relative Thermal Activity Curves of a Group of Thermostat Metals.

formulas 7-17 to 7-23, inclusive, and also other pertinent physical data of use to design engineers. Further comment on these would be superfluous.

In Fig. 7-16 are given the relative thermal-activity curves of some of the thermostat metals listed in Table 7-3. These characteristic curves give the relative movement of any type of element with temperature. These curves give the following information: Straight portions of the curves indicate uniform linear thermal movement, curved

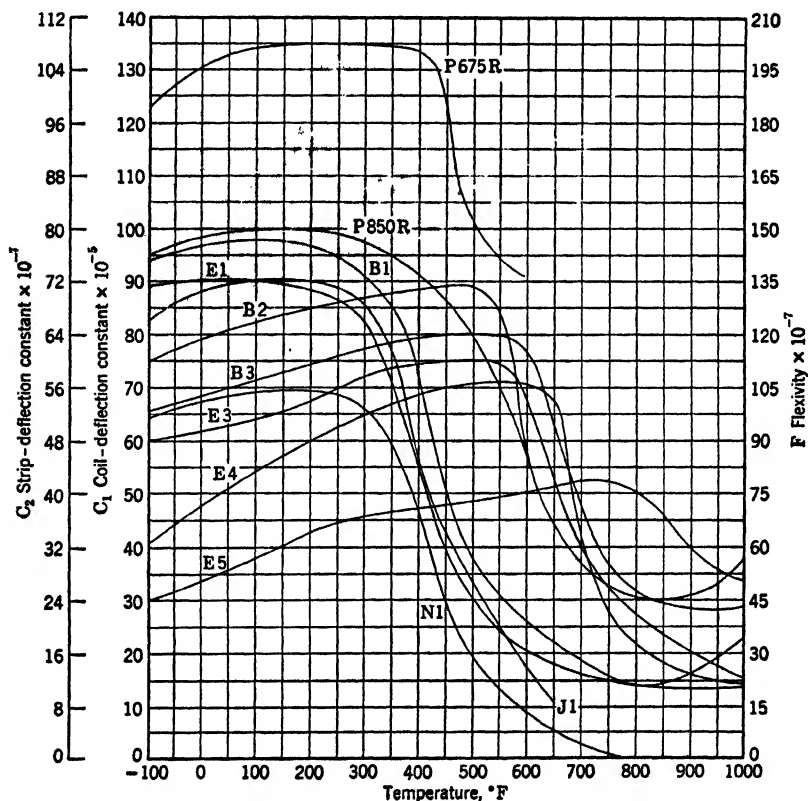


FIG. 7-17. Thermal Activity Constant versus Temperature.

portions indicate nonuniform or nonlinear movement, and the steepness or slope of the curves indicates the magnitude of the movement. These curves are valuable in choosing the type of material for a particular use. For instance, for an application calling for relatively straight-line operation between 300 and 750°F the type E4 would be the logical choice.

Since the relative thermal activity curves are not linear, the thermal activity constants will vary with the particular temperature range chosen. In Fig. 7-17 are given the thermal-activity-constant versus

temperature curves. The flexivity, strip-activity constant, and coil-activity constant can be expressed by the same curve, using different ordinates, since they all express the same function (the first derivative of the relative thermal-activity curve) for various shapes of elements. These curves, therefore, give the instantaneous values of the constants.

#### STANDARD TOLERANCES

Standard tolerances for physical dimensions and some properties are given in Table 7-4.

TABLE 7-4. TOLERANCES

Thickness, in.	Tolerance, in.	Width, in.	Tolerance, in.
0.005-0.010	$\pm 0.00035$	0- $\frac{1}{2}$	$\pm 0.004$
0.010-0.015	$\pm 0.0004$	$\frac{1}{2}$ -1	$\pm 0.005$
0.015-0.020	$\pm 0.0005$	1-3	$\pm 0.006$
0.020 and up	$\pm 2\frac{1}{2}\%$	3-5	$\pm 0.010$
		5-8	$\pm 0.015$
Length, ft	Tolerance, in.		
0-1	$\pm \frac{1}{32}$		
1-3	$\pm \frac{1}{16}$		
3-6	$+\frac{1}{2}, -\frac{1}{16}$		

Edgewise or camber curvature  $\frac{1}{32}$  in. per foot.

Flexivity (and other thermal activity constants)  $\pm 4$  per cent.

Electrical resistivity  $\pm 3$  per cent.

Throughout this paper, an attempt has been made to concentrate on thermostat metal itself rather than its uses and applications. A discussion of the large variety of applications would take several times the length of this article. The reader is referred to the extensive literature in current journals and in patents for this information.

The author wishes to express his appreciation to Mr. Paul G. Chace, manager of the Thermostat Metals Department, General Plate Division, Metals and Controls Corporation, Attleboro, Mass., for his suggestion that this paper be written and for his approval for having it published; and also to Mr. Raymond M. Sears, engineer of the same organization for assisting in compiling a large portion of the data appearing in the paper.

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## Aluminum-Clad Products

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Alclad products consist of an aluminum-alloy core covered on one or more sides with one or more thin surface layers of corrosion-resistant aluminum or aluminum alloys. The thickness of the coating on each surface is usually  $2\frac{1}{2}$  to 10 per cent of the total thickness of the product. The aluminum-alloy coating and core combinations are selected so that in corrosive environments the coating is anodic to the core and, hence, exerts electrolytic protection over exposed areas, such as cut edges, scratches, or spots uncovered by corrosion or abrasion.<sup>1</sup>

The word "alclad" was originally registered by the Aluminum Company of America as a trademark to cover products of the type just described, but in the interest of allowing industry-wide use of this name, the company subsequently relinquished the trademark rights. The alclad designation is used universally throughout the aircraft industry. Government specifications use the word "clad." The Reynolds Metals Company employs the words "clad" or "Pureclad," the latter identifying a pure aluminum coating.

The full cross section of a piece of Alclad 24S-T4(-T)\* sheet 0.040 in. thick<sup>2</sup> is shown in the micrograph of Fig. 8-1. The surface layers of pure aluminum appear light in contrast to the more deeply etched 24S-T4(-T) core. Figure 8-2 shows a section<sup>3</sup> through the surface of a piece of Alclad 17S-T4(-T)† which had been deeply scratched and then exposed outdoors at New Kensington, Pa., for 6 years. No corrosion has occurred in the alloy core uncovered by the scratch be-

\* Revised Alcoa Temper Designations are used throughout this chapter. Old designations, when different, are shown in parentheses.

† An alloy similar to 24S-T4(-T) which has been largely replaced by the latter alloy.

cause of the electrolytic protection offered by the alclad coating. Note the sacrificial attack of the coating adjacent to the scratch.

Alclad products are to be preferred over nonclad aluminum products wherever maximum resistance to corrosive conditions is desired. There

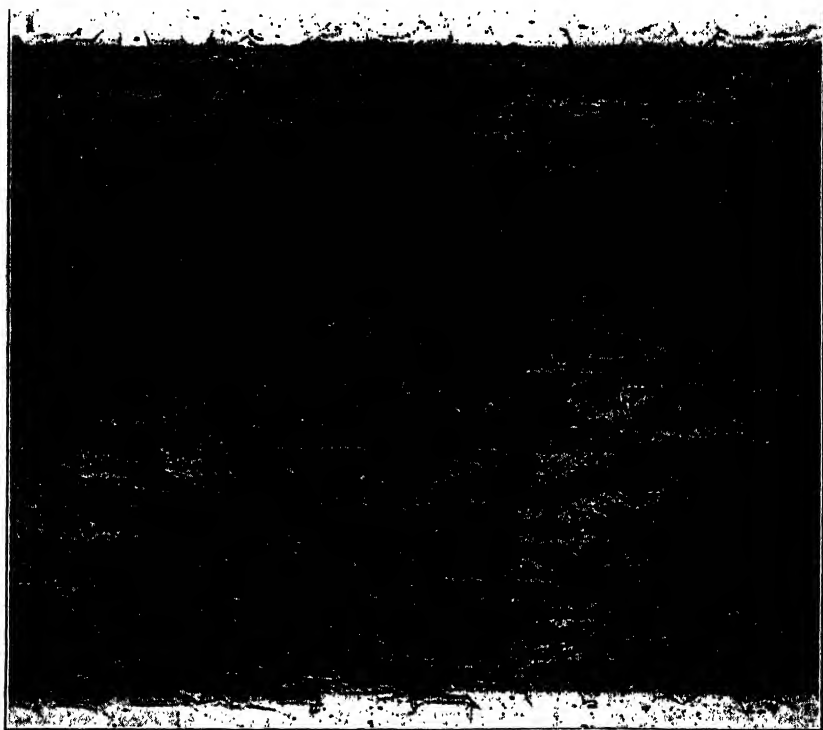


FIG. 8-1. Full Cross Section of 0.040-in. Alclad 24S-T4(-T) Sheet. Mag. 100 $\times$ . Etched: HF-HCl-HNO<sub>3</sub> solution 15 sec. Etching differentiates between surface layers of high-purity aluminum and 24S-T4(-T) core. Diffusion zones, resulting from migration of copper and magnesium into the coating layers, are evident.

are two general alloy classifications of the products: (a) alclad heat-treatable alloys, which maintain their strength even under severely adverse corrosive conditions, and (b) alclad non-heat-treatable alloys, which resist perforation and so provide leakproof surfaces. An example of the use of products of the former classification is that of the familiar bright unpainted surfaces of the commercial transport planes in this country. Gasoline and water tanks illustrate an application of products of the latter classification.

## COMMERCIAL PRODUCTS

Alclad products in the United States are, at this time, produced commercially only as sheet, plate, tubing, and wire. Alclad extrusions have been produced experimentally, but difficulties in maintaining a suffi-

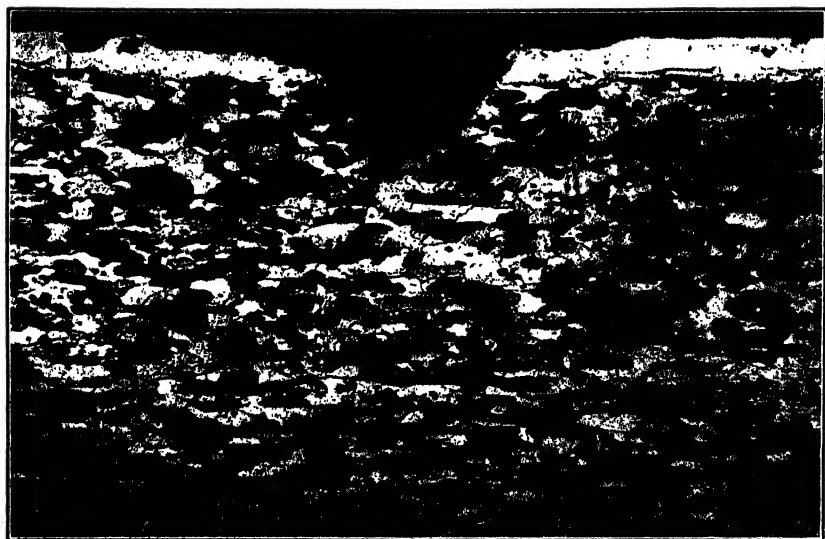


FIG. 8-2. Electrolytic Protection of Core of Alclad Sheet. Mag. 100 $\times$ . Etched: HF-HCl-HNO<sub>3</sub>. Cross section of Alclad 17S-T4(-T) sheet (0.040 in. thick) showing electrolytic protection of core exposed by deep scratch. No corrosion of core occurred during 6 years' exposure to New Kensington atmosphere. Note sacrificial attack of coating adjacent to scratch.

ciently uniform coating thickness to meet the requirements of most applications have not been overcome. Coatings on irregular shapes may be produced by metal spray, but the present cost of the process has limited its application.

The first commercial product of the alclad type was Alclad 17S sheet produced by the Aluminum Company of America for the aircraft industry<sup>4,5</sup> in 1928. Since then, millions of pounds of alclad strong aluminum-alloy sheet and plate have been produced.<sup>6</sup> It has been estimated that during the war about three quarters of the strong aluminum-alloy sheet used in U. S. aircraft was an alclad product. Alclad non-heat-treatable alloy sheet and tubing and alclad screen wire have been used in sufficient quantities to have established their value.

The chemical, physical, and mechanical characteristics of commercial alclad sheet and plate are listed in Tables 8-1, 8-2, and 8-3. Table 8-1

TABLE 8-1. CHEMICAL COMPOSITION OF ALCLAD PRODUCTS

	Cu	Si	Mn	Mg	Zn	Cr	Al
Alclad 3S							
Coating (72S)					1		
Core (3S)			1.2				
Alclad 14S							
Coating (53S)		0.7		1.3		0.25	
Core (14S)	4.4	0.8	0.8	0.4			
Alclad 24S *							
Coating (Al)							99.3 †
Core (24S)	4.5		0.6	1.5			
Alclad 75S							
Coating (72S)					1		
Core (75S)	1.6			2.5	5.6	0.3	
R301 ‡							
Coating		0.7	0.5	1.0			
Core	4.5	1.0	0.8	0.4			

\* This product as manufactured by Reynolds Metals Co. is designated "Pureclad" 24S.<sup>26</sup>

† Minimum.

‡ See reference 14.

gives the chemical composition of the coating and core alloys, Table 8-2 the coating thickness, and Table 8-3 the mechanical properties.

TABLE 8-2. NOMINAL COATING THICKNESS OF ALCLAD SHEET AND PLATE

	Thickness Range of Products, in.	Coating Thickness, % of total
Alclad 3S	*	*
Alclad 14S	0.020-0.039	10
	0.040 and over	5
Alclad 24S	0.010-0.063	5
	0.064 and over	2.5
Alclad 75S	0.016 and over	4
R301	0.024 and under	10
	0.025-0.039	7.5
	0.040-0.101	5
	0.102 and over	2.5

\* Not standardized. Coating thickness of 5 and 10 per cent of total thickness on one or both sides, depending on thickness and application, have been used.

Alclad 3S is a non-heat-treatable product used where high resistance to perforation is required without the necessity of the high strength of the heat-treatable alloys.



TABLE 8-3. MECHANICAL PROPERTIES OF COMMERCIAL ALCLAD SHEET AND PLATE

Alloy	Form	Thickness, in.	Tensile Strength, psi		Tensile Yield Strength, psi (Offset = 0.2%)		Elongation in 2 in., %		Compressive Yield Strength, psi (Offset = 0.2%)	Shearing Strength, psi	Modulus of Elasticity, psi Tension and Compression	
			Typical	Minimum	Typical	Minimum	Typical	Minimum			Primary	Secondary
Alclad 3S-O	Sheet	All thicknesses	16,000	.....	6,000	.....	30	..	6,000	11,000	10,000,000	
Alclad 3S-H14(-1/2H)	Sheet	All thicknesses	21,000	.....	18,000	.....	8	..	18,000	14,000	10,000,000	
Alclad 3S-H18(-H)	Sheet	All thicknesses	29,000	.....	25,000	.....	4	..	25,000	16,000	10,000,000	
Alclad 14S-T4(-W)	Coiled sheet	0.020-0.039	59,000	55,000	37,000	32,000	20	15	39,000	37,000	10,500,000	
		0.040-0.128	61,000	55,000	37,000	34,000	21	15	40,000	38,000	10,500,000	
Alclad 14S-T3(-W)	Flat sheet	0.020-0.039	59,000	55,000	38,000	35,000	18	14	41,000	38,000	10,500,000	
		0.040-0.249	62,000	57,000	40,000	37,000	20	15	44,000	40,000	10,500,000	
Alclad 14S-T4(-W)	Plate	0.250-0.500	62,000	57,000	40,000	37,000	19	15	44,000	40,000	10,500,000	
Alclad 14S-T6(-T)	Coiled or flat sheet	0.020-0.039	65,000	63,000	58,000	56,000	9	7	60,000	40,000	10,500,000	
	Plate	0.040-0.249	63,000	64,000	60,000	57,000	10	8	64,000	43,000	10,500,000	
		0.250-0.500	68,000	64,000	60,000	57,000	12	8	64,000	42,000	10,500,000	
Alclad 24S-T4(-T)	Coiled sheet	0.012-0.063	63,000	56,000	41,000	37,000	19	12-15	43,000	40,000	10,600,000	9,600,000
		0.064	65,000	60,000	42,000	38,000	20	13	44,000	41,000	10,600,000	10,100,000
Alclad 24S-T3(-T)	Flat sheet	0.010-0.063	64,000	59,000	43,000	39,000	17	12-15	46,000	41,000	10,600,000	9,600,000
		0.064-0.249	66,000	62,000	44,000	40,000	18	15-13	47,000	42,000	10,600,000	10,100,000
Alclad 24S-T4(-T)	Plate	0.250-0.500	66,000	62,000	44,000	40,000	18	11	47,000	42,000	10,600,000	10,100,000
Alclad 24S-T36(-RT)	Flat sheet and plate	0.022-0.063	67,000	62,000	53,000	48,000	11	8-10	57,000	43,000	10,600,000	9,600,000
		0.064-0.500	70,000	66,000	55,000	50,000	11	10-9	59,000	44,000	10,600,000	10,100,000
Alclad 24S-T31	Flat sheet	0.010-0.063	66,000	62,000	60,000	54,000	7	5	61,000	40,000	10,600,000	9,600,000
		0.064-0.249	69,000	65,000	63,000	56,000	7	5	64,000	41,000	10,600,000	10,100,000
Alclad 24S-T36	Flat sheet	0.022-0.063	70,000	66,000	66,000	62,000	6	3	57,000	42,000	10,600,000	9,600,000
		0.064-0.249	73,000	70,000	69,000	66,000	6	3	70,000	43,000	10,600,000	10,100,000
Alclad 70S-T6(-T)	Sheet and plate	0.018-0.039	76,000	70,000	66,000	60,000	10	7	68,000	46,000	10,400,000	9,800,000
		0.040-0.499	77,000	72,000	67,000	62,000	11	8	70,000	46,000	10,400,000	9,800,000
R301-T4(-T)	Sheet	0.039 and under	59,000	56,000	39,000	37,000	19	14	.....	.....	10,300,000	
		0.040 and over	61,000	57,000	41,000	37,000	20	15	.....	.....	10,300,000	
R301-T6(-T)	Sheet	0.039 and under	60,000	53,000	61,000	54,000	8	7	62,000	43,000	10,300,000	
		0.040 and over	69,000	64,000	61,000	57,000	9	8	62,000	43,000	10,300,000	

All values supplied by Aluminum Company of America, except those for R301 which were obtained from R301—Reynolds' New High Strength Aluminum Alloy, by T. L. Fritslen and L. F. Mondolfo, *Metals and Alloys*, 30, 4 (Oct. 1944).

The range of properties available in alclad strong alloy sheet<sup>7</sup> is well illustrated in Fig. 8-3. In this chart the alclad products have been located so that the specified minimum yield strength falls on a straight line. This chart is of considerable interest when it is remembered that the sheet that was used for most military planes in the last war was

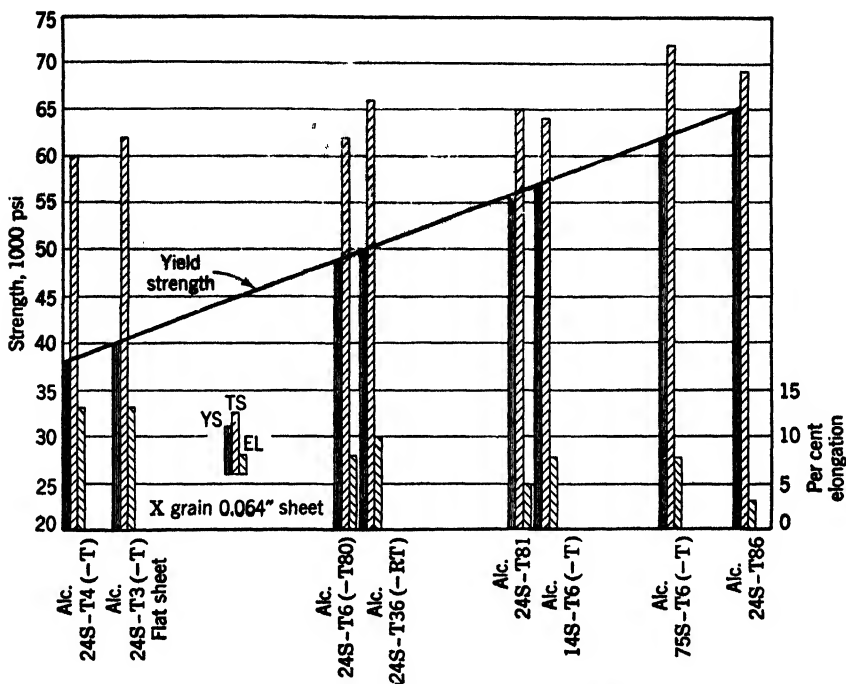


FIG. 8-3. High-Strength Aluminum Alloy Alclad Sheet (Minimum Specification Values).

Alclad 24S-T3 or -T4(-T) and -T36(-RT), whereas near the end of the war the higher-strength products became available to the aircraft industry and were being used in the new designs.

#### METHOD OF BONDING COATING AND CORE

The metallurgical bond between the coating and core in alclad products is obtained by a process which is essentially pressure welding. The first commercial sheet and plate were produced in the United States by a "casting process" in which composite ingots were made by casting a high-strength aluminum alloy between slabs of wrought aluminum.<sup>1</sup>

The initial bond thus obtained was completed by hot rolling. With the development in the aluminum industry in this country of much larger ingots made by the continuous-casting process it was found for most products to be more economical to use a "rolling process" in which the wrought slabs were fastened mechanically to the strong alloy ingot and the bonding accomplished entirely by hot rolling.

The thickness of the slabs is proportioned to that of the ingot to give the desired percentage of coating on the finished sheet. The movement of the metal in rolling breaks up the oxide film on the surfaces of the cast ingot and wrought slabs and the temperature and pressure are sufficient to accomplish complete welding of the surfaces. The integral metallurgical character of the bond obtained is proved by the fact that, during subsequent thermal treatments, the alloying elements in the core diffuse into the coating and those in the coating diffuse into the core. This interdiffusion presents one of the problems in the manufacture and heat treatment of alclad products in that it must be carefully controlled in order to maintain the desired composition difference between coating and core.

Before the end of the war the German industry had adopted the casting method using long coating slabs as the sides of the mold in the continuous casting process.

### RESISTANCE TO CORROSION

The resistance of aluminum to corrosion is high and thoroughly adequate for most applications. However, the addition of certain alloying elements such as copper, required to give the higher strength for many structural applications, lowers the resistance to corrosion so that protective measures are generally advisable. The alclad strong alloy products combine the advantages of the high strength of the core and the high resistance to corrosion of the coating. In addition, however, the coating electrolytically protects the exposed areas of the core. Hence, under corrosive conditions, the corrosive attack proceeds only to the interface between the coating and core and then spreads out without penetrating into the core wherein the strength of the product resides. As an example of the effectiveness of the alclad protection, specimens of Alclad 17S-T4(-T) sheet 0.035 in. thick exposed in the ASTM<sup>a</sup> atmospheric exposure tests suffered no loss in strength even after 10 years' exposure at the most severe seacoast location, La Jolla, Southern California. In contrast, similar specimens of 17S-T4(-T) lost about 50 per cent in tensile strength after 10 years at this location.

The resistance to perforation of aluminum alloys of high resistance to corrosion is also greatly improved by an alclad coating offering electrolytic protection to the core. Aluminum and its corrosion-resistant alloys owe their resistance to a thin ever-present oxide film. However, under corrosive conditions, weak spots in the film break down, and corrosive attack of the metal starts. Under some conditions of exposure this attack becomes highly localized and, with thin sections, may result in perforation. However, in the alclad product, as previously explained, the attack spreads out at the interface, and perforation is prevented for a long period of time.

### CATHODIC PROTECTION

The electrolytic action just described is generally known as "cathodic protection." Because of the importance of cathodic protection in the service performance of alclad products it is essential that the mechanism be thoroughly understood.

The components of an electrolytic cell are the two metallic electrodes (the anode and the cathode) and the electrolyte (corrosive solution). In such a cell, the direction of the current flow is from the anode through the electrolyte to the cathode. The anode dissolves sacrificially and protects the cathode from attack. The degree of cathodic protection afforded by the anode over the cathode depends on the quantity of current. Other conditions being constant, the magnitude of the current flow is determined by the difference between the "electrode potentials" of the anode and cathode; however, polarization effects may be important in limiting the current.

### ELECTRODE POTENTIALS

The effect of alloying elements on the electrode potentials of aluminum alloys as measured against a common reference electrode is given in Table 8-4.<sup>9</sup> From this table it may be observed that some alloying elements such as manganese, or magnesium and silicon in the ratio of the compound  $Mg_2Si$ , have no important effect on the electrode potential of aluminum. However, certain other elements such as copper, when in solid solution in an aluminum alloy, lower the electrode potential, that is, make the alloy more cathodic; whereas magnesium and zinc, in solid solution in aluminum, raise the electrode potential, that is, make the alloy more anodic. These and other elements, when used within certain ranges, will form alloys suitable for alclad coatings on the usual aluminum-base alloys.<sup>10, 11</sup>

In corrosive environments the coating of higher-solution potential is anodic and will protect the core of the more cathodic alloy of lower-solution potential.

TABLE 8-4. ELECTRODE POTENTIALS OF ALUMINUM SOLID SOLUTIONS AND CONSTITUENTS \*

	Volts
Al + 1% Zn solid solution	-0.96
Al + 4% Mg solid solution	-0.87
Aluminum	-0.84
Al + 1¼% Mn	-0.83
Al + 1% Mg <sub>2</sub> Si solid solution	-0.83
Al + 4% Cu solid solution	-0.66
CuAl <sub>2</sub>	-0.53

\* In aqueous solution containing 53 grams NaCl + 3 grams H<sub>2</sub>O<sub>2</sub> per liter, 0.1 N calomel scale.

As an example, it may be seen that, in a sodium chloride-hydrogen peroxide solution, pure aluminum is anodic to an aluminum-copper alloy containing about 4 per cent copper in solid solution by about 0.15 volt. Extended service experience in a variety of corrosive conditions has indicated that this difference in solution potential is adequate to give very satisfactory electrolytic protection of exposed areas of the core and at the same time is not sufficiently great to cause too high sacrificial attack of the coating. It is of interest that, in the ASTM test previously mentioned, the Alclad 17S-T4 (-T) specimens showed no greater loss in weight than the commercially pure aluminum specimens. This would not have been so if too great difference in potential between coating and core had existed, for then the excessive sacrificial corrosion of the coating would have caused greater weight loss.

In the case of Alclad 3S, the core contains, as an alloying element, only about 1¼ per cent manganese. Thus, its potential is about the same as that of pure aluminum. Consequently, a pure aluminum coating would not electrolytically protect the 3S core. Electrolytic protection, however, is achieved by employing a coating of an alloy known as 72S, which contains about 1 per cent zinc.<sup>10</sup> This same alloy is employed as coating for the high-strength aluminum-alloy product,<sup>12, 18</sup> Alclad 75S.

Coatings of aluminum-manganese or aluminum-manganese-magnesium alloys have been employed in Germany in combination with cores of the high-strength aluminum-copper alloys. Also, heat-treatable alloys of the 53S type, containing Mg<sub>2</sub>Si as the principal alloying addition, are now being employed commercially in the United States

in the sheet products R301<sup>14</sup> and Alclad 14S. This coating alloy responds to the same heat treatments as the 14S core and, hence, offers a harder stronger coating than pure aluminum, with almost as good resistance to corrosion.

### THERMAL TREATMENTS

In Table 8-5 are listed some of the currently available sheet and plate alclad-type products, with the typical coating and core electrode potentials.

TABLE 8-5. COATING AND CORE ALLOY ELECTRODE POTENTIAL RELATIONS \*

Product	Typical Electrode Potential, volts †		
	Coating	Core	Difference
Alclad 3S	-0.96	-0.83	0.12
Alclad 24S-O	-0.83	-0.83	0
Alclad 24S-T4(-T)	-0.83	-0.68 to -0.70 ‡	0.15 to 0.13
Alclad 24S-T81	-0.83	-0.80	0.03
Alclad 14S-O	-0.83	-0.79	0.04
Alclad 14S-T4(-W)	-0.80	-0.68 to -0.70 ‡	0.12 to 0.10
Alclad 14S-T6(-T)	-0.83	-0.78	0.05
Alclad 75S-O	-0.96	-0.94	0.02
Alclad 75S-W	-0.96	-0.88	0.08
Alclad 75S-T6(-T)	-0.96	-0.81	0.15

\* R. H. Brown, Aluminum Research Laboratories.

† In aqueous solution containing 53 grams NaCl + 3 grams H<sub>2</sub>O<sub>2</sub> per liter; 0.1 N calomel scale.

‡ Depending on quenching rate.

### ALCLAD ALUMINUM-COPPER ALLOYS—14S AND 24S

The thermal treatment of the alclad aluminum-copper alloys is discussed in detail in the following paragraphs. A later section covers any differences in behavior of the alclad aluminum-zinc-magnesium-copper alloy 75S.

It may be observed from Table 8-5 that the difference in potential between coating and core of the alclad products having an aluminum-copper-type alloy core ranges from 0 to 15 millivolts. The reason for this range is to be found in the potential of the core which varies from -0.68 to -0.83 volt. To understand the reason for this difference in core potential it is necessary to review briefly the heat treatment and tempers of aluminum-copper alloys of this type. It should be borne in mind that the electrode potential is determined primarily by the amount of copper in solid solution in the aluminum.

In the annealed temper (the symbol O is used to designate the annealed temper of all of the wrought aluminum alloys) most of the copper is out of solution so that the core potentials range from  $-0.79$  to  $-0.83$ . Sheet in the annealed temper is used to permit severe forming operations and should be heat-treated before being put in service.

#### SOLUTION HEAT TREATMENT

The heat treatment used to impart the high strength and hardness to the aluminum-copper alloys consists in heating at a suitable temperature in the range of  $915$  to  $960^{\circ}\text{F}$  for a sufficient length of time to put the copper in solid solution. This is known as "solution heat treatment." The alloy is then rapidly cooled to room temperature by quenching. If the cooling is sufficiently rapid, most of the copper is retained temporarily in solid solution. However, the solid solubility of copper in aluminum at room temperature is less than about 0.05 per cent, compared to approximately  $4\frac{1}{2}$  per cent at the temperature of the solution treatment. Precipitation of some of the aluminum-copper constituent from the supersaturated solid solution is believed to occur in a very fine and uniformly dispersed form during 2 or 3 days subsequent to quenching. The precipitate is submicroscopic, and its exact nature not definitely known. However, the electrode potential does not change during this period although the strength and hardness increase and the elongation decreases. The aging at room temperature is known as "natural aging." The symbol -T3 or -T4(-T) is used to designate this temper for 24S and -T3 or -T4(-W) for 14S.

#### QUENCHING

It will be noted that in Table 8-5 the electrode potential of the core for these alloys in the naturally aged temper is  $-0.68$  to  $-0.70$  volt. The variation is caused by differences in the rates of cooling during quenching. Sufficiently rapid cooling to produce an electrode potential of  $-0.68$  volt can be achieved under commercial conditions by quickly immersing thin sections in cold water after the solution heating. If the section thickness is over about  $\frac{1}{8}$  to  $\frac{1}{4}$  in., or if the individual pieces are not spaced so as to permit free circulation of water during the quenching, the cooling rate will be slower, and the electrode potential will approach  $-0.70$  volt. A similar condition will exist if other quenching practices which produce slower cooling rates than cold-water immersion are employed. Apparently, during the slower cooling localized gross precipitation occurs, often at the grain boundaries, thus raising the potential.

It is often necessary to form parts of strong aluminum-alloy sheet in the annealed temper and subsequently heat-treat them. If the parts are quenched by immersion in cold water which, in the case of certain of the alloys is desirable in order to obtain maximum resistance to corrosion, excessive distortion occurs, and reshaping the formed parts is necessary. This is an expensive operation. Consequently, there is a desire to quench at a slower rate so as to avoid or minimize distortion. Such practices lower the resistance to corrosion of aluminum-copper alloys in the naturally aged temper and are not recommended for a non-alclad product. The slow quenching, as previously stated, causes localized precipitation, often at the grain boundaries. The areas where such precipitation has occurred are depleted in copper and, therefore, anodic to the remaining solid solution and particles of precipitate. Thus, the alloy is susceptible to intergranular corrosion. In the artificially aged temper slower quenching rates are permissible, as is explained in later paragraphs under the heading "Artificial Aging."

With naturally aged alclad products, the slow rate of quenching has a less deleterious effect on resistance to corrosion. It is true that the core material is affected by selective precipitation, but, in the absence of excessive diffusion, the coating is not affected. It still acts as a cover to prevent corrosive media from reaching the core. Electrolytic protection is, however, much less effective than with a rapidly quenched product because of the higher electrode potential of the core. The degree of protection varies considerably with the thickness of the product and the extent of diffusion. Excessive diffusion not only raises the potential of the coating, thus further decreasing the potential difference between coating and core, but also causes the coating in slowly quenched sheet to be susceptible to intergranular corrosion. For thin sheet, diffusion must be carefully controlled or slow quenching should be avoided.

#### ARTIFICIAL AGING

The strength and hardness of 24S and 14S can be further increased by "artificial aging," that is, an aging treatment at a temperature in the range of 300–400°F for a period of 6 to 12 hr, depending on the alloy and temperature. This artificial aging promotes gross precipitation, with a resultant increase in strength, especially yield strength, and hardness, accompanied by a decrease in elongation. The temper thus achieved in 14S is designated by the symbol -T6(-T). In 24S, the response to artificial aging is influenced by the amount of cold working which the product has received subsequent to the solution treatment.



The artificially aged temper of 24S is indicated by the generic symbol -T8. A second digit is added to indicate approximately the amount of cold working which the product has received; thus, 24S-T81 represents artificially aged commercial flat sheet in which the flattening process subsequent to the solution treatment has introduced approximately 1 per cent cold work.

From Table 8-5 it may be noted that the electrode potentials of the artificially aged tempers range from  $-0.78$  to  $-0.80$  volt, and the differences in electrode potential between the coating and core are small compared with the rapidly quenched and naturally aged temper. Complete electrolytic protection may not be obtained in marine environments if the difference in potential between coating and core is only 5 millivolts or less.

Artificial aging of a rapidly quenched alloy of the 14S type brings about localized gross precipitation, generally at the grain boundaries, and a susceptibility to intergranular corrosion. If artificial aging is continued until precipitation of substantially all of the copper from solid solution has occurred, the difference in the electrode potentials of the grains and grain boundaries is eliminated, and the alloy is no longer susceptible to intergranular corrosion. However, this treatment overages rapidly quenched thin sections of 14S and greatly decreases its strength.

Artificial aging is not harmful to the resistance to corrosion of 14S which has not been rapidly quenched and may even cause some improvement. This is an advantage, because slower quenching rates to avoid distortion are permissible, and also thicker sections which, because of their mass cool more slowly even when immersed in cold water, have their resistance to corrosion improved by artificial aging. However, the artificial aging does reduce the difference in electrode potential between coating and core and so reduces the effectiveness of the electrolytic protection (see Table 8-5).

In the product Alclad 24S-T81, artificial aging may be carried to the point where almost complete precipitation occurs in the grain centers as well as the grain boundaries, without having a detrimental effect on the mechanical properties. Figure 8-4 shows how the potential of the grain centers approaches the potential of the grain boundaries<sup>25</sup> with prolonged aging at  $375^{\circ}\text{F}$ . It may be noted, however, that if this practice is employed the potential of the core is substantially the same as that of the coating so that no electrolytic protection of the core can occur.

## DIFFUSION

The diffusion of the alloying elements from the core into the coating and, in the case of the alloy coating, from the coating into the core, has already been mentioned. The extent of diffusion is a function of both time and temperature. The rate of diffusion below about 650°F is relatively slow<sup>16</sup> so that little diffusion is obtained even for long times

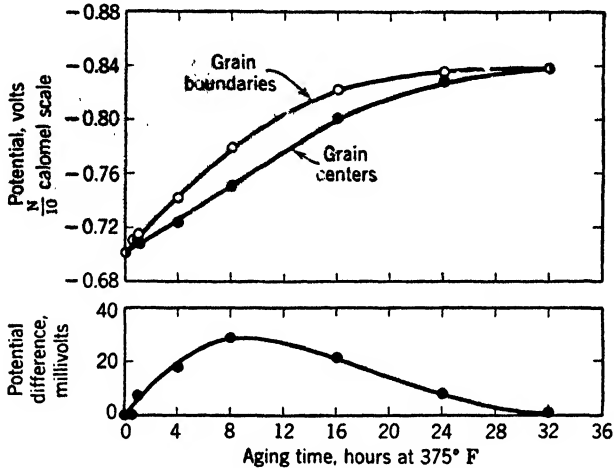


FIG. 8-4. Effect of Reheating on the Solution Potentials of Grains and Grain Boundaries of High-Purity Binary Aluminum-Copper (4.10 per cent) Alloy. (Courtesy R. H. Brown, Aluminum Research Laboratories)

of heating. Above about 800°F the rate of diffusion is much more rapid and the control of the time more critical.

The thinner the section, the more necessary it is to keep diffusion to a minimum. Regardless of thickness, diffusion will proceed a fixed distance for any time-temperature condition. This distance will be a higher percentage of the coating thickness in thin sheet than in thicker sheet. A time-temperature condition which would not cause excessive diffusion in thick sheet might cause harmful diffusion in thin sheet. For this reason, the coating thickness is a greater percentage of the total sheet thickness for the thinner gages of 14S, R301, and 24S than for thicker sheet. Thicker coatings are employed on 14S and R301 because, with thinner coatings, excessive diffusion might cause the coating to be susceptible to intergranular corrosion in the artificially aged -T6(-T) temper.

The control of diffusion is a vital factor in obtaining the highest resistance to corrosion in alclad products. Annealing in the usual temperature range of 650–800°F causes very little diffusion. Excessive diffusion during the solution treatment is avoided by limiting the soaking time to the minimum required to give specified mechanical properties. The number of permissible reheat treatments depends on the thickness of the sheet and the percentage coating thickness.<sup>17</sup>



FIG. 8-5. Schematic Cross Section of Alclad 24S-T4(-T) Sheet. Sketch illustrates characteristic diffusion zone. Diffusion is more rapid at grain boundaries of coating.

The appearance of the diffusion zone in Alclad 24S-T4(-T) sheet is shown diagrammatically<sup>18</sup> in Fig. 8-5. Note also the diffusion zone in the micrographs of Figs. 8-1 and 8-2. It may be observed that the diffusion proceeds more rapidly along the grain boundaries of the pure aluminum coating. The copper content of the diffusion zone is not uniform but is highest immediately adjacent to the alloy core and tapers to a minimum at the edge of the diffusion zone. Although the

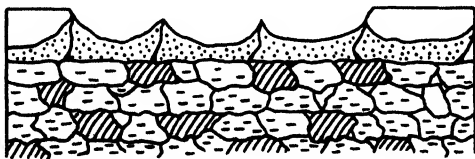


FIG. 8-6. Schematic Cross Section Showing Superficial Corrosion. Sketch illustrates electrolytic protection of diffusion zone by the more anodic pure aluminum.

necessity of controlling the extent of diffusion in order to obtain maximum resistance to corrosion has been emphasized, a limited diffusion zone performs a valuable function. Its electrode potential is intermediate between that of the pure aluminum coating and the 24S-T4(-T) alloy core. Therefore, under corrosive conditions it offers a second barrier against the progress of corrosion. Figure 8-6 diagrammatically illustrates surface corrosion which has extended only to the diffusion zone.<sup>18</sup> The micrograph of Fig. 8-7 shows an actual case of light-gage

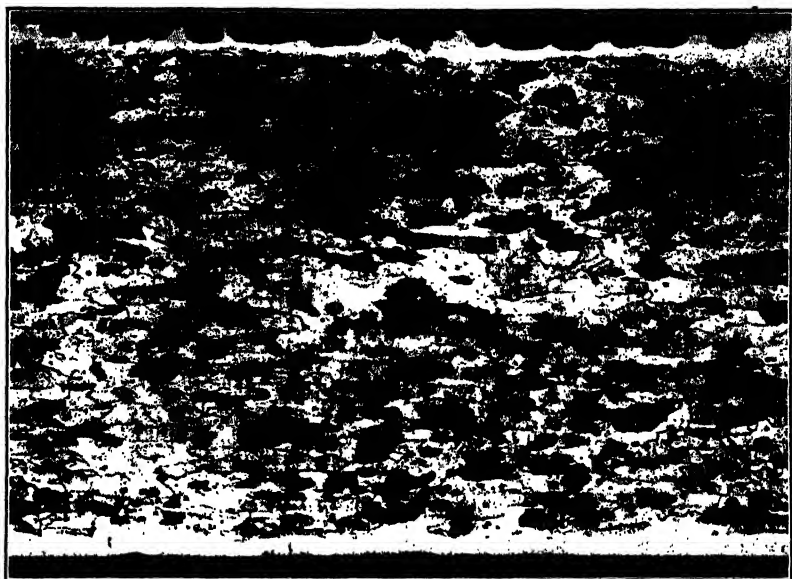


FIG. 8-7. Superficial Corrosion of Surface of Alclad Sheet. Mag. 100 $\times$ . Etched: HF-HCl-HNO<sub>3</sub>. Full cross section through 0.027-in.-thick Alclad 24S-T4(-T) air-plane-wing skin corroded on inside surface (upper in micrograph) from exposure to engine exhaust fumes and moisture. The corrosion attack penetrated only to diffusion zone. The peaks in the corroded coating correspond to the peaks in the diffusion zone illustrated in Figs. 8-5 and 8-6. Electrode potential of diffusion zone is intermediate between that of the pure-aluminum coating and the 24S-T4(-T) alloy core; hence, under corrosive conditions it offers a second barrier against the progress of corrosion.

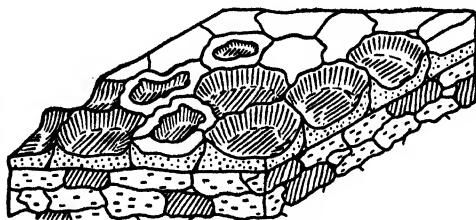


FIG. 8-8. Schematic Block Diagram of Superficially Corroded Surface of Alclad 24S-T4(-T) Sheet. Sketch illustrates "peak and valley" appearance of corroded surface.

Alclad 24S-T4(-T) sheet with superficial corrosion extending to the diffusion zone caused by engine exhaust fumes and moisture.<sup>18</sup>

Corrosion will not proceed any deeper until the pure aluminum has been removed over a considerable area. Then the diffusion zone will electrolytically protect the core, and corrosion of the core will not occur while substantial areas of the diffusion zone remain. The crater-like appearance of the surface in alclad sheet after such surface corrosion may be observed through a magnifying glass. It is illustrated schematically <sup>18</sup> in Fig. 8-8. When this condition is noted, it may be concluded with assurance that corrosion of the core has not occurred.

#### ALCLAD ALUMINUM-ZINC-MAGNESIUM-COPPER ALLOY—75S

The electrode potential of 75S, an aluminum alloy containing zinc, magnesium, and copper, also depends to a considerable extent on the thermal treatment which it has received, but the changes are more complicated than in the aluminum-copper alloys, because zinc and magnesium in solid solution have an effect on electrode potential opposite to that of copper. Zinc and magnesium when put in solid solution by the solution heat treatment raise the electrode potential, whereas copper in solid solution lowers it.

The resistance to corrosion of Alclad 75S-T6(-T) is less influenced by the rate of quench. However, since the mechanical properties of this alloy are influenced by slow quenching to a greater extent than the resistance to corrosion, slow-quenching practices cannot be tolerated. The effect of diffusion is much less important in this product, because the diffusion of the zinc and magnesium into the coating tends to offset the effect of the diffusion of copper into the coating, and, hence, the electrolytic protection is assured with any thermal practices which produce the specified minimum mechanical properties.

Artificial aging of 75S to produce the -T6(-T) temper causes precipitation of all three elements, but the precipitation of the magnesium and zinc lowers the potential, and that of the copper raises it. After a solution treatment, 75S ages naturally for a number of months. The strength and hardness increase, and the ductility decreases. Hence, the alloy is seldom left in this temper (designated -W) but, instead, is artificially aged to the -T6(-T) temper. No change in electrode potential is detected during natural aging. Typical electrode potential values for the O, -T4(-W), and -T6(-T) tempers are given in Table 8-5.

## MECHANICAL PROPERTIES

The mechanical properties of an alclad product are determined essentially by those of the core material. The pure aluminum coatings contribute little to the strength of the product. However, heat-treated alloy coatings, such as are employed for R301-T6(-T) and Alclad

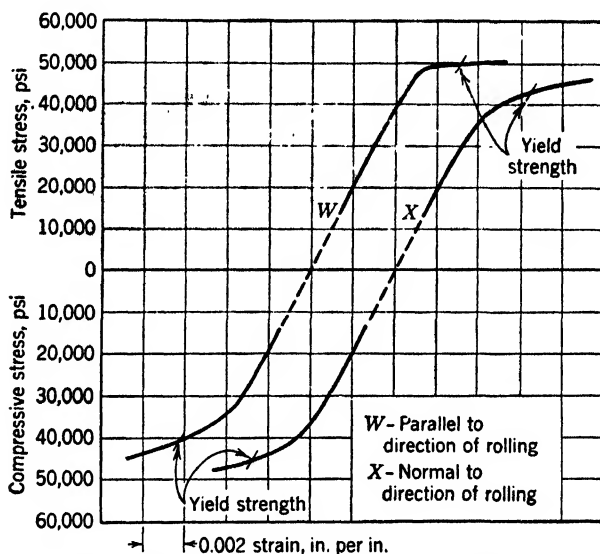


FIG. 8-9. Typical Stress-Strain Curves for Alclad 24S-T3(-T) Sheet.

14S-T6(-T), contribute to the strength of the product to an appreciable extent.

The typical and minimum-specification mechanical properties for the commercial alclad products are given in Table 8-3. The difference in properties shown for the different thickness ranges of sheet is caused by the different percentage coating thickness. For example, the coating on each surface of Alclad 24S-T3 or -T4(-T) sheet in thicknesses less than 0.064 in. is 5 per cent of the total sheet thickness; for gages 0.064 in. and greater, the coating is only 2½ per cent of the total thickness. The differences in properties between Alclad 14S-T4(-W) coiled and flat sheet "-T3"(-T) and between Alclad 24S-T4(-T) coiled and flat sheet "-T3"(-T) are the result of the effect of cold work introduced after the solution heat treatment by the flattening operations which generally include stretching.

### MODULUS OF ELASTICITY

Figure 8-9 shows typical stress-strain curves of Alclad 24S-T3(-T) sheet.<sup>19</sup> The first part of these curves up to approximately the yield strength of the pure aluminum coating in either the tension or compression has a slope typical of the nonalclad sheet. However, after the yield strength of the coating is reached, the slope of the curves changes somewhat. The moduli corresponding to these two slopes are called the primary and secondary moduli of elasticity of the alclad products.

R301 and Alclad 14S-T6(-T), because of the higher yield strength of the heat-treated alloy coating, do not exhibit a determinable difference between primary and secondary moduli.

The difference between the primary and secondary modulus of elasticity is of relatively little significance in design calculations; that is, there is no appreciable added penalty in weight over that caused by the lower yield strength of the alclad products.

### FATIGUE STRENGTH

The fatigue characteristics of alclad products require special consideration. An alclad sheet specimen subjected to repeated flexure in a fatigue-testing machine will show an endurance limit at 500,000,000 cycles about 25 per cent lower than that of the nonalclad product. In such tests the outer fibers, that is, those of the alclad coating, are subjected to the greatest deformation. When a specimen which has been subjected to this type of test is examined microscopically, large numbers of fatigue cracks may be observed in the pure aluminum coating. However, the coating does not spall nor check.

In contrast to these laboratory fatigue tests, service experience has not indicated that the apparently lower fatigue strength of alclad products places a limitation on their usefulness in comparison with other aluminum-alloy products. It seems probable that the protective effect of the pure aluminum coating, as regards notch effects from both corrosion and abrasion, may more than compensate for the lower inherent fatigue characteristics of the coating material. The softer coating also tends to "damp out" vibrations.

### FORMABILITY

The more ductile coatings on the alclad sheet products definitely give increased formability to these products. The improved formability has been demonstrated in many manufacturing operations.

## MAGCLAD SHEET

The principle of alclad protection developed for aluminum-alloy products has been applied to clad-magnesium-alloy sheet.<sup>20-25</sup> The highest-strength magnesium sheet alloys contain aluminum and zinc. These elements lower the solution potential of the magnesium to the extent that pure magnesium or the commercial magnesium-manganese alloys will be anodic to these stronger alloys and may be used as coating materials. These products have been made experimentally in sufficient quantities to have been subjected to accelerated and outdoor exposure tests. These tests have demonstrated the superior resistance to corrosion of such products.

The more extensive use of the high-strength magnesium-alloy sheet has been limited by its susceptibility to stress-corrosion cracking. It has been demonstrated that coatings anodic to the higher-strength magnesium alloys produce immunity to stress-corrosion cracking of these products. Therefore, the commercial development of clad-magnesium-alloy sheet products offers the most promising solution to this otherwise troublesome problem.

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## Hot-Dipped Aluminum-Coated Steel

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Aluminum coating or aluminizing is a relatively new method of applying a nonferrous protective coating to a metal, usually iron or steel, by the hot-dipping process. The iron or steel, after being suitably prepared,<sup>1</sup> is passed through a bath of molten aluminum alloy, and the coating is allowed to solidify on the surface. This coating can be applied to sheets, strip, and wire.

Aluminum owes its corrosion resistance to the existence of a self-renewing surface oxide film which forms in normal atmosphere. Under many conditions the aluminum coating, like zinc, affords galvanic or electrolytic protection on bare spots by sacrificing itself as anode to reduce corrosive attack of the exposed-steel base metal, the cathode.

Aluminized steel has the advantage of combining the surface characteristics of aluminum with the mechanical properties of iron and steel. The aluminum coating provides the corrosion resistance, heat resistance, heat reflectivity, and attractive appearance of aluminum; the base metal gives the strength of iron or steel.

**Base Metals.** The aluminum coating is applied commercially to mild steel, copper steel, and low-alloy high-strength steel. When sheet steel is needed for superior drawing qualities and more uniform workability, drawing quality may be specified.

Table 9-1 shows the relative physical properties of aluminized steel after coating.

**Coating Weight.** The weight of an aluminum coating on sheet or strip is expressed in ounces per square foot of sheet area. The weight of coating on aluminized steel sheet or strip is approximately 0.50 oz per square foot. The coating thickness is approximately 0.001 in. per side or 0.002 in. over-all on sheet and strip. This is equivalent in

thickness to approximately a 1.30-oz coating of zinc, the difference in coating weights being due to the different specific gravities of the two metals.

**Fabrication.** Aluminized steel can be fabricated by all of the conventional processes, including punching, shearing, and forming on a press brake. Moderate drawing or stamping can be accomplished also with aluminized steel if the article to be drawn or stamped is designed with large radii to relieve friction, strain, and sharp corners. Such drawing should be done on a slow-action press.

TABLE 9-1

	Low-Carbon Steel Base	High-Strength Steel Base
Yield point	30,000 psi	50,000-60,000 psi
Tensile strength	45,000 psi	65,000-80,000 psi
Elongation in 2 in.	15-25	12-20
Rockwell B	70 max.	70-85 max.

Aluminized steel can be joined by any one of several methods, that is, double seaming, arc welding, seam or spot welding, oxyacetylene welding, atomic hydrogen arc welding, and brazing. Certain precautions are necessary in performing welding operations on aluminized steel similar to those employed in the joining of aluminum. Excessive oxidation of the coating during the welding operation must be prevented, and in the case of spot and seam welding it is desirable to remove the aluminum oxide film on the surface prior to welding. Soldering can be performed by pre-treating the edges to be joined. Specific recommendations for procedures are available from the manufacturer on request.

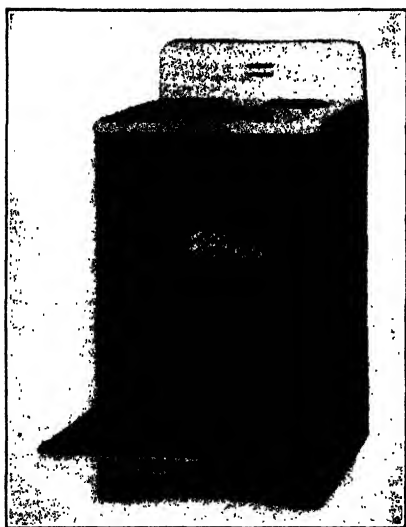


FIG. 9-1. Oven Linings for Kitchen Ranges.

**Heat Resistance.** The heat resistance of aluminum-coated

steel can be described as follows: Up to about 900°F, the coating gives complete protection to the steel without discoloration. Above this temperature, the coating reacts with the steel base to form an alumi-

num-iron alloy which is tightly adherent and highly refractory. Tests have shown that this aluminum-iron alloy completely protects the steel base from oxidation and scaling during short exposures to temperatures as high as 1750°F.

**Heat Reflectivity.** Fabricated aluminized steel will serve as an efficient and stable heat and light reflector. The superior heat-reflecting quality is preserved by the resistance of the aluminum coating to oxidation and heat discoloration.

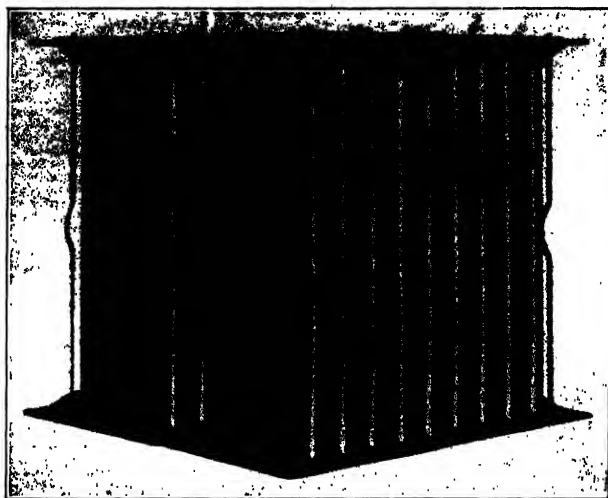


Fig. 9-2. Core of Gas-Burning Industrial Unit Heater.

Superior heat-resisting and heat-reflecting characteristics make aluminum-coated sheets desirable for oven linings (Fig. 9-1), where heat reflectivity and resistance to scaling are significant factors. Such fabricated parts serve equally well in units heated with electricity, gas, oil, or solid fuels.<sup>2</sup>

**Atmospheric Resistance.** Aluminum-coated steel is comparatively new, and atmospheric corrosion tests are not yet of sufficient duration to supply complete data on atmospheric resistance properties.

However, 4-year atmospheric exposure tests in a mild industrial atmosphere have shown aluminized coating to lose approximately one tenth as much weight as galvanized coatings under the same conditions. Two-year exposures in a marine atmosphere show aluminized coatings to lose approximately one fifth as much weight as galvanized coatings. Although aluminum coatings in the atmosphere do not offer the same

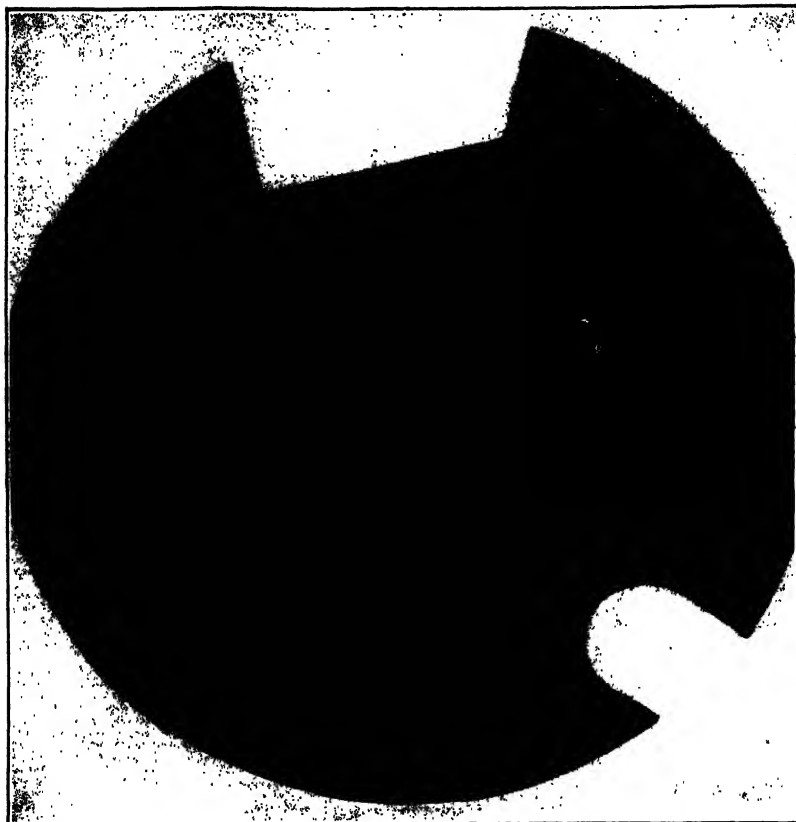


FIG. 9-3. Airplane Fire Wall.

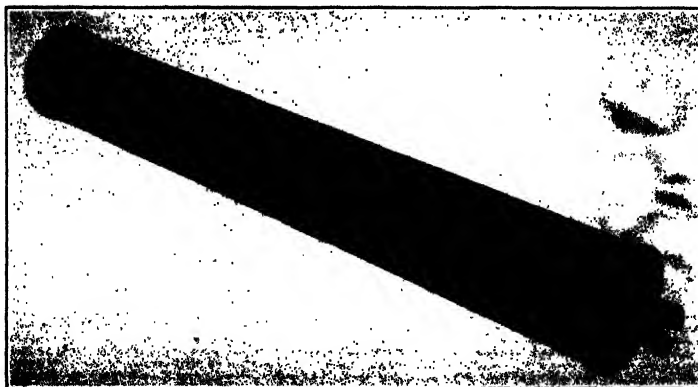


FIG. 9-4. Automobile Muffler.

galvanic protection at sheared edges as zinc coatings, the edge rusting of the aluminized samples in the afore-mentioned tests has not been serious.

**Possible Uses.** Aluminized steel today fills a recognized need for a relatively low-priced heat-resistant sheet metal. In circulating heaters of advanced design (Fig. 9-2) the drums or inner jackets are being made of this material to resist the destructive effects of high temperatures.

Aluminized steel has been used successfully in the aircraft industry to replace more critical material in firewalls and accessories<sup>a</sup> (Fig. 9-3).

Tests conducted on gasoline-engine mufflers (Fig. 9-4) and tail pipes of aluminized steel have shown noteworthy increase in life over such materials as hot-rolled, cold-rolled, and terne-coated sheets. Such service demands a combination of corrosion and heat resistance.

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## Copper and Copper-Alloy Clads

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### HISTORY

The art of cladding one metal with another is probably as old as the practice of alloying one metal with another. In both cases the original underlying "reason for being" was undoubtedly economy. Ancient metal workers developed methods of "sweating" thin layers of gold or silver onto a base of copper or brass, thus making their supply of precious metal stretch further, just as did the maker of King Hiero's crown, until exposed by Archimedes.

Later, however, cladding (as well as alloying) was adopted for reasons other than conservation or economy, although this basic thought still predominates in the field of gold, silver, stainless steel, nickel, Monel, and related clad metals. It was found that certain metals, clad with certain other metals, possessed physical properties and engineering advantages that were unique and could not be obtained with any single solid metal or alloy. In this class fall the copper- and copper-alloy-clad steels.

Generally speaking, clad metals are not new, and, although copper-clad steel wire was firmly established by the beginning of the first World War, there was very little commercial production of copper- and copper-alloy-clad strip and sheet, at least in the United States, until the beginning of World War II. In the patent literature, a method of uniting iron with copper by heating juxtaposed slabs and then *pressing* them together was described in a patent issued in 1867. In 1881 the making of a copper-clad iron by *hammering* a packet, composed of heated iron and copper sheets, was described. In this same year, first mention was made of *rolling* together crimped sheets of copper and iron, but it was not until 1901 that the idea of inserting copper or copper-

alloy slabs into a preformed steel billet and then heating and rolling this assembly to strip was conceived. This method, with modifications, forms the basis of one of the important present-day manufacturing practices.

Although there were many other arts and methods developed during this period, little appears to have been done to reduce these inventions to commercial practice, with one exception. About 1905, the Duplex Metals Company was organized at Chester, Pa. This company equipped itself primarily for the production of copper-clad steel wire, its plant containing casting, hot-rolling, and cold-drawing machinery. The process used was based on first dipping a billet of steel in molten copper in order to form an iron-copper alloy on the surface, then placing this coated billet in a mold somewhat larger than itself, and pouring molten copper completely around the core. On solidification, this was rolled to bars and wire rods. Mention is made that copper-clad strip and sheets were also produced. A rather complete description of this process appears in the September 12, 1912, issue of *The Iron Age*. We understand that this company went out of business in 1914.

Around 1915 another method of producing copper-clad steel wire was brought to commercial status. This method did not use the preliminary dipping of the steel in molten copper before casting and thus minimized the formation of a copper-iron alloy so detrimental to high conductivity. Because of the superior electrical characteristics of this new material, it found immediate acceptance in industry, being especially useful in rural transmission lines. This material is available today under the trade name "Copperweld." This method of cladding, however excellent for the production of round shapes, did not lend itself too well to the production of flat rolled products such as sheet or strip.

Europe, however, driven by necessity and shortages of nonferrous metals, was producing copper-alloy-clad steel in sheet form before and after the first World War. This material was used in small-arms ammunition components, especially the bullet jacket. Steel, clad with copper alloy, known as tombac, was produced at the Skoda Works in Czechoslovakia, France, England, and various other countries, by the "pack-rolling" method. In this method, slabs of precleaned copper alloy and steel were placed face to face, wrapped in sheet steel, with the edges crimped to exclude air, heated, and rolled on sheet mills until bonding was effected and the pack reduced to desirable thickness. The cover sheets were then dissolved in acid and the clad metal further reduced by cold rolling. This clad metal was the standard material for bullet jackets in all the countries of Europe, and in England and



China. Not only did the use of this clad save copper, but it was claimed that the bullet jacket was superior to that made from solid copper alloy. In the United States, however, bullet jackets were made from a solid 90 per cent copper, 10 per cent zinc alloy, and in Canada, for obvious reasons, a solid 80 per cent copper, 20 per cent nickel (cupronickel) was used.

Shortly after the outbreak of World War II in Europe in 1939, foreign purchasing commissions began to look for a source of tombac clad strip steel in the United States. Their demands were enormous—the European pack-rolling method could not begin to produce the requirements. In addition to this copper became scarce, and shortly afterwards nickel was placed on the critical list. At this point a strip-steel manufacturer came forward with a method of producing a copper-alloy-clad steel strip, known as “gilding metal clad.” This method was based on practices developed earlier for the production of stainless clad steel but was so modified and made so practical that any plant with hot- and cold-strip mills could easily adopt it for tonnage production. Copper or copper-alloy strip steel, made by this simplified practical method, is now on the market under the trade name “SuVeneer.” \* It did not take the Allies and the United States long to adopt “gilding-metal-clad steel” for ammunition components. Hundreds of thousands of tons of this material was produced, releasing great quantities of copper and zinc for more vital uses. At about this same time another method was brought out which consisted of pressing slabs of gilding metal and steel together while they were being heated under a reducing atmosphere. This pressing effected bonding; the slabs were later rolled to desired dimensions. This process supplemented the rolling method previously described.

During this wartime period, copper-alloy-clad steel strip was used primarily to conserve strategic materials. Fortunately, however, although the emphasis was on high production for one specific purpose, there was some interest in these clads in other fields. Tests were made on the practicability of copper-alloy-clad strip for bearings, in radio, and for a multitude of other uses, most of which, it must be admitted, were substitutions for solid copper alloys. However, enough interest was shown by consumers to encourage the development of clads of all kinds and to place the copper-clad strip industry on a firm footing. The copper-clad steel-wire industry, being firmly established at the outbreak of the war, was in position to aid tremendously in the war effort.

\* Trade-mark registered U. S. Patent Office by Superior Steel Corporation.

"Copperweld" wire was used in a great many ways, a few of which were fencing, reinforcing wire for concrete, ground rods, nails, staples, cable rings, pipe-wrapping wire, wall ties, antennas, and applications where nonsparking characteristics were important.

At the present time many types of copper- and copper-alloy-clad steels are on a commercial basis, although, as with other types of clads, an attempt is being made to standardize coating thicknesses and types rather than to "tailor-make" a great many different grades. The potentialities of copper- and copper-alloy-clad materials, both strip and wire, have not as yet been fully realized. At present, experiments are in progress to determine the properties of this material for use in electrical, thermal, mechanical, and chemical applications. Clads differ in many ways from plated or dipped coatings—each has its place in industry, and only time will reveal the true usefulness of the copper and copper-alloy clads.

#### METHODS OF MANUFACTURE

Copper and copper-alloy clads are manufactured in several different ways, each method having certain advantages and disadvantages. The most successful methods in use today are casting, pressing, and straight rolling. A fourth system which has possibilities is sintering powdered metals on a base of strip steel.

#### CASTING

In this method a round cleaned steel billet is placed on end in a mold somewhat larger than itself and heated as a unit under reducing conditions, and then molten copper or copper alloy is poured around the steel-core piece. After solidification the clad billet is reheated and rolled to round shapes, such as bars and wire rods. After cleaning the wire rods are heat-treated and cold-drawn to wire. The great strength imparted by the steel core in combination with the electrical properties of the surrounding copper make this material of great value in rural electrification. The corrosion resistance of the copper together with the strength of the steel makes it additionally useful.

Another method of making clads by casting is based on forming a recess or boxed space on top of a slab of steel and then pouring molten alloy into this space so that on solidification a bonded layered slab results. This can be reheated and rolled to desired dimensions, resulting in sheets of copper- or copper-alloy-clad steel. With this method it is possible to produce clads that are incapable of being hot-rolled, by

cold rolling only. Likewise, this method can be used in the production of clads with practically any proportion of cladding to base metal, which is not the case with some of the other methods.

### PRESSING

In this method a layered pack of steel and copper or copper-alloy sheets, properly prepared, is built up on a base. A furnace, equipped with controlled atmosphere, is placed over the stack, and pressure is applied to the top of the stack while heat is applied. The combination of heat and pressure effects bonding between adjacent faces. Of course, separating compounds are applied between those faces that are not part of each composite layer. These bonded composites are later reheated and rolled to sheets and are slit, if desired, to strip sizes.

This method has many advantages because it enables the production of many types of clads in a great variety of cladding thicknesses. Here again, it is possible to proportion the individual layers so that hot rolling can be eliminated, and thus non-hot-workable clads can be produced, finishing the bonded assemblies to size by cold rolling only. This method is not particularly adapted to heavy tonnage production but is a very versatile one and has distinct possibilities.

### ROLLING

This method proved invaluable during the last war in the production of great quantities of clad steel strip required for the manufacture of ammunition components. Slabs of copper alloy were fastened to both sides of precleaned steel sections, and the resulting composite billet was heated and rolled to strip. The strip was then cold-rolled to desired dimensions and tolerances. This method resulted in long heavy coils ideally suited to automatic machines. The disadvantage of this method is that percentages of cladding are necessarily limited to certain ranges. Because bonding is effected during hot rolling, extra heavy claddings cannot be made, owing to the difference in plasticity between copper and steel at the rolling temperatures, which causes thinning of the copper during the first few passes. After bonding has taken place, however, the two metals maintain their respective thicknesses, regardless of the nature or extent of subsequent work.

Of the three methods discussed, the "Copperweld" casting method is particularly well suited for the production of wire and bars in quantity. It is difficult to produce strip from round composite castings because during flattening in a hot strip mill much of the cladding goes to the edges and is lost if sheared, while the remaining varies in thickness

across the width of the strip within rather wide limits. The box casting on flat slabs is better adapted to production of sheet but does not appear to be especially suitable for economical quantity production.

The second method, pressing, has the advantage of forming the bond before hot rolling, which enables the cladding of alloys with low melting points. Once the bond is formed, the composite slab can be hot-rolled at any temperature that will not melt the cladding metal and still allow the steel to be reduced in thickness. On a sheet mill this temperature can be appreciably lower than on a strip mill. The disadvantage of this method is that it produces rather short lengths and is not well adapted for the production of coils of strip so useful on automatic machines. It is not adaptable for the production of rounds.

The third method, rolling, is ideal for the production of large quantities of long-length coils of strip of standard clad types on a hot strip mill. It is not too well suited for the production of clads with low melting points, inasmuch as the bond is formed during rolling, by heat and pressure, and the success of rolling is dependent on the workability of the steel within the temperature limitations imposed by the melting point of the cladding metal. It is not suitable for the production of wire or round shapes.

It must be remembered, in all three of the methods discussed, that, in most cases, the cladding metal must be capable of withstanding hot work, and, for light-gage materials, cold work also, although, by using special technique in the flat or box-casting or pressing methods, the hot-working step might possibly be eliminated.

#### SINTERING

A method of making clads which consists of spreading powdered metal over the surface of steel strip, and then sintering by passing it through a controlled-atmosphere furnace has been developed. It is possible to form special types of cladding on steel by this method. Instead of one powdered metal layer, two or more might be used in order to obtain special properties, or, if desired, mixtures of powdered metals might be applied. Rolling, after sintering, is sometimes imposed in order to obtain gage accuracy. This method is particularly well adapted for the production of strip for bearing applications.

#### DEPOSITION \*

A method has been described wherein copper or copper alloy is deposited on the surface of a steel strip from a welding rod by means of a

\* See Chapter 14 for a discussion of welding methods.

gas flame into which is introduced a flux. After deposition, the clad strip may be rolled. Although this method is hardly competitive with the other systems for economical production, it is very useful and has a place in industry.

#### PROPERTIES OF COPPER- AND COPPER-ALLOY-CLAD METALS

##### BOND

As is evident from the foregoing discussion of methods of manufacture, copper and a great many of the copper alloys can be firmly bonded to iron or steel by means of heat and pressure alone or by the casting of molten alloy on or around steel. Unlike stainless steels and some alloys which form a refractory surface film on heating, absolute exclusion of air between layers prior to pressure bonding is not essential, although it is well to take steps to minimize oxidation of either component during heating.

The exact nature of the bond formed is not too well known at present, but it undoubtedly varies with the method of manufacture. In most cases it appears to be both mechanical and intermolecular. In the "heat and pressure" bond, there is but little evidence of the formation of actual alloys of iron and the facing metal, but in the casting method there is definite penetration and alloying of the facing metal with the base metal. In any event, regardless of the physical or chemical nature of the boundary area, the two metals are inseparable after bonding, unless, of course, blisters caused by impurities or gases are present. The only practical way of separating a copper or copper-alloy facing layer from the underlying steel core is by chemical solution of one metal or the other. Mechanical or thermal separation is impossible. Properly made copper- or copper-alloy-clad steels can be bent, drawn, twisted, punched, sheared, spun, flanged, heated and quenched, upset, or otherwise formed without any separation whatsoever.

The bond is ductile, and it is not unusual to cold-roll  $\frac{1}{8}$ -in.-thick hot-rolled copper-clad steel strip down to 0.005-in. strip, with suitable intermediate anneals without any separation or failure. As high as 85 per cent cold reduction by rolling has been applied to annealed copper-clad steel strip without an intermediate anneal and again with no sign of failure of the bond. In this latter case, the copper cladding on the 0.005-in. finished clad strip was only 0.0005 in. thick on each side. Moreover, it was continuous and nonporous. Cold drawing of hot-rolled wire rods to fine wire causes no separation whatever.

## TYPES OF CLADDING MATERIALS

It is difficult to list the numerous kinds of copper- and copper-alloy-clad steels that can be manufactured by one method or another. However, if consideration is given to limitations imposed by (1) melting point, (2) surface characteristics after heating, and (3) hot workability, the following are suitable for bonding to steel by the "rolling" (strip) process: oxygen-free high-conductivity copper (99.9+ per cent copper), phosphor deoxidized copper (99.9+ per cent copper), special deoxidized copper (99.9+ per cent copper), gliding metal (95 per cent copper, 5 per cent zinc), commercial "bronze" (90 per cent copper, 10 per cent zinc), some of the nickel silvers (copper-nickel-zinc alloys), and the two standard cupronickels (80 per cent copper, 20 per cent nickel, and 70 per cent copper, 30 per cent nickel). Some of the tin brasses (such as manganese bronze) can be successfully bonded although the melting point is quite low, making hot working difficult. Various grades of copper are commonly used in the production of clad wire, being chosen primarily for their electrical characteristics and corrosion resistance.

Copper-zinc brasses containing between 10 and 36 per cent zinc are not usually recommended for hot working although some of these brasses, for instance, 70-30, have been successfully clad to steel. Evidently the steel lent needed support during hot working and prevented checking and cracking. The alpha-beta brasses hot-work well but are not too well suited for cold working, and, because they possess a low melting point, little work has been done on cladding them to steel.

Leaded brasses, because of their poor hot-working properties, cannot be clad by the hot-rolling process, nor can silicon bronzes and aluminum bronzes, because these appear to take on a refractory oxide film when heated in the presence of air, which effectively prevents bonding to steel. Very possibly, if care were taken to prevent surface oxidation, no difficulty would be encountered. The tin bronzes, such as 95 per cent copper, 5 per cent tin and 92 per cent copper, 8 per cent tin, although possessing excellent cold-working properties, have a very narrow hot-working range as well as a relatively low melting point and are not ordinarily clad to steel.

It is quite possible that these previously mentioned alloys which are not suitable for cladding by the rolling process can be successfully clad by other methods, such as deposition, casting, or pressing. It would be best to check on this with the companies using such methods.

In passing, it might be well to mention that Monel, nickel, and silver can be successfully clad to steel by the rolling method, and the pressing method is particularly well adapted for the production of silver-clad steels. Also, various types of stainless steel can be clad to steel if care is taken to prevent the formation of oxide layers on the contacting faces of the components.

#### CORE MATERIALS

The previously mentioned copper and copper alloys can be clad to low-, medium-, or high-carbon or alloy steels by the rolling or casting method. For deep drawing and similar work requiring core metal of high ductility, regular low-carbon deep-drawing steel, rimmed or killed, is generally used. If greater strength is desired, medium-carbon or alloy steel is used. If spring properties, high hardness, or great strength is required, a high-carbon or alloy steel is used. Heat treatment is used to develop the required properties in the core, this treatment usually having little or no effect on the properties of the cladding layer and no damaging effect whatever on the bond between the two metals. Properly clad material will withstand all the processing operations, such as annealing, pickling, and cold rolling, that are ordinarily applied to unclad steels; in fact, the cladding serves as protection against such damaging effects as decarburization of high-carbon steel, gas embrittlement during pickling, and similar undesirable reactions.

#### PERCENTAGE OF CLADDING

One of the major strip-mill producers of copper- and copper-alloy-clad steels has recently set up standard limits on the thickness of cladding, the width range, and the thickness range on commercial types of clads manufactured by the rolling method. These limits are, at present, 10 per cent by thickness on each side, known as 10-10, hot-rolled, 0.095 in. to 0.312 in. thick up to  $10\frac{1}{4}$  in. wide; cold-rolled, 0.015 in. to 0.095 in. thick up to  $10\frac{1}{4}$  in. wide, for copper, gilding metal, commercial "bronze," and the cupronickels clad both sides of low-carbon deep-drawing steel. For the same alloys clad one side only, known as 10-0, on low-carbon steel, the condition and thickness limitations are the same up to 10 in. wide. For copper and commercial "bronze" on medium- to high-carbon steel, grades available are 10 per cent each side and 10 to 15 per cent one side up to 5 in. wide, thickness and condition depending on "end use." Standards have not been established for the nickel silvers or other special alloys.

For a complete discussion on the types available and characteristics of copper-clad steel wire, see page 548, *Metals Handbook*, 1948 edition, published by the American Society for Metals.

Limitation standards for products made by other methods are not available at the present time but can be obtained from manufacturers using those methods.

### CORROSION RESISTANCE

Inasmuch as a clad metal presents a continuous nonporous face of the nonferrous metal to the action of corrosive agents, the *initial* corrosion resistance, at least, of a clad metal will be the same as that of a solid nonferrous metal of the same analysis unless the cladding layer is scratched, pitted, or removed in some manner, so that the underlying steel is exposed. It must be appreciated that resistance to corrosive agents is present only as long as a continuous layer of the cladding metal is present. Sheared edges, punched holes, and such that expose the steel will, of course, be points of weakness unless protected in some manner as by soldering, painting, or plating.

Solid copper, gilding metal, and commercial "bronze" have been used for years to resist atmospheric corrosion. Steel clad with these metals should be satisfactory. Solid cupronickel has excellent resistance to sea-water attack. Cupronickel clads might be used as substitutes.

### STRENGTH AND HARDNESS

Values for tensile strength, various yield strengths, and elongation obtained in tensile testing of copper- and copper-alloy-clad steels depend on several factors: (a) type of steel core and condition, that is, carbon or alloy content, annealed, cold-rolled, heat-treated, etc.; (b) type of cladding metal and condition; (c) relative proportions of cladding and core metal. It would be impossible to list all the values obtainable, considering these three major variables, but it may be said, in general, that the *tensile and yield strengths* are generally close to a calculated weighted sum of the strength of the components taken separately. For example, if a 10-10 double-clad commercial "bronze" on low-carbon deep-drawing steel annealed strip is being considered, the specimen will consist of 20 per cent by thickness of a 90 per cent copper, 10 per cent zinc alloy and 80 per cent by thickness of steel.

The tensile strength of a solid 90-10 copper-zinc alloy in the annealed condition is approximately 38,000 psi, and that of a low-carbon annealed steel is 45,000 psi. The tensile strength of the clad metal will be close to the sum of  $(0.20 \times 38,000) + (0.80 \times 45,000)$  or 43,600 psi.



The bond between the two metals exerts, perhaps, a very slight influence on tensile strength. On the other hand, if this same commercial "bronze" were clad both sides of a high-carbon steel strip, 10 per cent by thickness each side, and the clad metal were then heat-treated to develop high strength in the steel, that same treatment would serve to anneal the cladding metal, and the tensile strength of the whole would be less than that of solid steel of similar analysis. For example  $(0.20 \times 38,000) + (0.80 \times 160,000) = 135,600$  psi for the composite. In this type of clad, mention should be made that the presence of the cladding may influence the rate of heat dissipation during quenching and thus alter the strength values of the steel. This influence is not great, and only certain shallow-hardening steels might be affected. As a third example, if commercial "bronze" were clad on both sides of low-carbon steel, 10 per cent by thickness each side, and the clad strip were then cold-rolled full hard, the steel core would attain a tensile strength of 90,000 psi, while the "bronze" would only possess a strength of about 70,000 psi, if taken separately. The clad would have a tensile value of approximately 86,000 psi.

Many other examples might be given; in fact, a table might even be constructed, but such a table would be superfluous. The calculation is simple, because the tensile values of the clads are usually, in the case of copper and copper-alloy clads, at least, the sum of the values of the two components taken separately and proportionately.

#### ELONGATION IN TENSION

It is unfortunate that the elongation values do not follow the same simple rule. The "bond effect" appears to have greater influence on this value than on the strength values. For example, if the core metal is low-carbon steel, annealed, with an elongation in 2 in. value of 35 per cent and the cladding is commercial "bronze" with 45 per cent elongation, the value of the clad metal is not the weighted sum of the two—it is generally closer to the value of the preponderant metal; that is, the steel, and the elongation value will be about 35 per cent instead of 37 per cent as might be expected. This is the case, at least, when the cladding metal has greater elongation than the core metal. When the reverse is true, as in the case of AISI type 430, stainless-clad and low-carbon steel, having, respectively, solid values of 25 and 45 per cent, the bond effect becomes greater, and a 10-10 clad of this nature will show 30 per cent elongation, which is again not the average of the two taken separately. Evidently, the less ductile metal, in separating first in the tension test, causes the more ductile metal to break along with

it. Careful work is indicated on this subject and might serve to clarify the entire mechanism of the strength and elongation values of clad metals.

For the present, at least, it might be said that the elongation values of clad metals do not follow any particular simple rule and should be obtained, for design purposes, on the specific type and condition of clad metal being considered.

## HARDNESS

Care must be taken in measuring and reporting the hardness of clad metals, especially the copper and copper-alloy clads. The cladding metal is generally softer than the underlying steel, regardless of the condition of the composites; that is, annealed, cold-rolled hard, or heat-treated. Although for most purposes the composite hardness of strip, measured by the Rockwell indenter pressing into the surface, will serve as a useful guide for repetitious work, this is not the true hardness—it is composite hardness, and the values obtained vary with the type and thickness of the cladding, the hardness of the base metal, and the weight on the indenter. "Anvil effect" plays a large part in determining the hardness of a clad metal, wherein a soft layer overlies a hard layer, unless the former possesses considerable thickness.

The true hardness of the cladding itself may be obtained by using very light weights, as with the Superficial Rockwell, Vickers, and similar systems, and the true hardness of the core is easily obtained by removing the cladding metal before making the measurement—grinding being as convenient a method as any. Chemical solution of the cladding may leave a surface on the underlying steel that will not result in true hardness readings. It is difficult to tabulate the hardness of clad metals—values for all the standard copper and copper alloys in all conditions are well known or can be obtained from standard references, as, for example, *Copper and Copper Base Alloys*, by Wilkins and Bunn, 1943, McGraw-Hill; the same is true of the hardness of various types of steel: *Metals Handbook*, 1948 edition, American Society for Metals; *Metals & Alloys Data Book*, S. C. Hoyt, 1943, Reinhold Publishing Company. As a matter of interest, however, copper itself usually varies in hardness from Rockwell B less than 0 in the soft condition to 60 hard. Gilding metal and commercial "bronze" vary from Rockwell B 0 to 70, cupronickel from B 35 to 85, and low-carbon steel from B 40 to 95. High-carbon steel can, of course, be annealed to about Rockwell B 80 and heat-treated to Rockwell C 60 or higher.

### OTHER MECHANICAL PROPERTIES

Ductility of copper-clad materials measured on the Erichsen or Olsen Machines is usually the same as for the underlying base metal—unclad. Values vary with type of steel core, condition, and thickness of sample.

In the deep drawing of strip steel, a 45 per cent reduction from blank to cup on the first draw is considered good safe practice. Copper-alloy-clad steels will withstand 50 per cent first draws without difficulty in commercial production. The reason for this is not too clear; perhaps the skin of copper alloy serves as a lubricant, reducing the amount of heat generated between the part and the die, thus reducing galling and seizing.

### THERMAL CHARACTERISTICS

Copper and copper-alloy clads are outstandingly useful in the thermal field. Next to silver, pure copper has the highest thermal conductivity of all the metals—a value of about 2700 Btu per hour per square foot per degree Fahrenheit per inch (32–212°F). The 90–10 commercial “bronze” has a value less than half this (1300) which is more than twice the value for iron and steel (460/470). The stainless steels lie in the range of 100/150.

However, wherein heat transfer is important, conductivity is not the whole story. Thermal conductance, which depends on conductivity; thickness of wall; and the conductances of gas, vapor, or liquid films; corrosion products and the like; is an important factor in the heat-transfer formula, which is generally given as  $H = U \times A \times dT$  where  $U$  is conductance in British thermal units per square foot per hour per degree Fahrenheit,  $A$  is available surface area in square feet, and  $dT$  is mean effective temperature difference in degrees Fahrenheit between the hot and cold fluids. Because film conductances play such a strong part in the value of  $U$ , the conductivity of a metal or alloy, *per se*, does not have too great an effect on the total amount of heat transferred through the bottom of, for instance, a pot or pan. Calculations and tests have shown that the time required to heat equivalent amounts of cold water to the boiling point in vessels made from different metals, alloys, or clad metals does not vary greatly. If we disregard this fact, however, and consider the “nature” of the heat transfer, we find that the metals with greater conductivities cause the heat to transfer through the metallic wall more uniformly and evenly. If conductivity is thought of as the ability to diffuse temperature—to spread it out

evenly—then it can be seen why a copper utensil will heat its contents better and with less sticking and burning of the contents than will, for instance, a utensil made from solid 18-8 stainless—flame conditions being equal.

Clad metals are recognized for their superiority in the cooking-utensil or heat-transfer field because of this ability to “diffuse” temperature differences. It may easily be seen that a stainless-steel utensil with a layer of copper bonded to the bottom—the copper taking up the heat from the source and diffusing it evenly—will present a uniformly heated inner surface to the contents of the vessel. A solid stainless utensil with its low inherent conductivity will possess areas of high and low temperature on the inner side of the heated wall. A tri-ply, consisting of copper next to the heat source, steel as a core, and stainless as the inner surface, the latter in contact with food or whatever, would be an ideal cooking utensil. The copper would receive the heat, diffuse it, transfer it to the steel (which has in itself fairly good conductivity), and thence uniformly and evenly apply the heat to the inner stainless layer. “Hot spots” would be impossible!

Still a third case would be a vessel consisting of stainless clad to both sides of a copper core. The advantages of a clad of this type are obvious, but the question is whether copper is required. Just how much conductivity is necessary to diffuse temperature differences in cooking utensils is unknown at present—perhaps a *steel* clad with stainless on each side would be good enough. These, however, are special cases in the clad-metal field and are a little off the subject.

An additional advantage of copper clads in the thermal field, besides their heat-diffusing properties, is that soldering, brazing, and so on are simple. Although the conductivity of a radiator core made from copper-clad steel might not be so good as solid copper, if clad were needed for additional strength, it could be assembled by much the same means as solid copper, that is, soldering by dipping, brazing, and so on.

Experiments have indicated that in calculating the thermal conductivity of copper and copper-clad metals the bond line has but little effect, and the conductivity is the weighted sum of the conductivity of the component metals. This is probably not the case where a definite alloy is formed between components or where an intermediate layer of some other metal is used between the major components for one purpose or another. For all practical considerations, the following values may be used as conductivity of the solid metals; pure copper 2700; 95 per cent copper, 5 per cent zinc, 1670; 90 per cent copper, 10 per cent zinc, 1300; 70 per cent copper, 30 per cent nickel, 200; 80 per cent copper,

20 per cent nickel, 260; and iron or steel 465—all in British thermal units per hour per square foot per degree Fahrenheit per inch. From these values can be easily calculated the conductivity of any combination. Obviously, if highest diffusing properties are desired in a clad metal, the cladding should be pure copper and should have appreciable thickness.

#### ELECTRICAL PROPERTIES

Not too much work has been done yet toward determining the electrical characteristics of copper- and copper-alloy-clad steel strip, although considerable data are available on the properties of "Copperweld" copper-clad wire. These properties are listed in the previously quoted reference (*Metals Handbook*, 1948, page 548) and will not be included here. However, it might be said that two grades of copper-clad wire are available commercially, the 30 and the 40 per cent grade. These designations mean that the clad wire has 30 and 40 per cent, respectively, of the electrical conductivity of a solid-copper wire of the same cross section.

On strip, it has been reported that on a clad consisting of 20 per cent of copper on each side of mild steel (40 per cent total by thickness or volume) the electrical conductivity was 45 per cent of that of solid copper. For d-c work, it would appear that the current-carrying capacity of a clad would depend to a great degree on the percentage of copper present, because of the different resistances of copper and steel. In high-frequency work, because of "skin effect," a different condition might obtain. Experiments are being conducted at present to determine these values.

In the electronics field, copper clads are coming into use. Certain types of copper clads are being tried out for sealing with glass in the manufacture of radio tubes. Copper clads have been tested in radio receiving sets as baffles and the like, because of their "shielding" effect. All these uses are too new to be discussed with any authority at the present time.

#### GALVANIC ACTION

The usefulness of zinc coatings on iron or steel lies in the fact that zinc sacrifices itself to corrosive influences, lying as it does above iron or steel in the galvanic table, and thus protects the core metal. Copper and the copper alloys, on the other hand, lie below iron and steel and thus will be protected by iron or steel when exposed to galvanic corrosive conditions. However, no galvanic action will take place between

the layers of copper and steel bonded together, as this action does not take place in the absence of an electrolyte, and there is, of course, no room for an electrolyte between the properly bonded layers of a clad metal. On the other hand, if the copper layer is penetrated or destroyed, one would naturally expect the underlying steel to be attacked, probably at an accelerated rate, because it would be anodic to the couple.

When copper- or copper-alloy-clad metals are used in conditions where galvanic action would be expected, the position of the cladding metal in relation to the other contacting metal should be considered.

### MELTING POINT

The core metal, usually iron or steel, of a copper or copper-alloy clad has a higher melting point than any of the copper or copper-alloy cladding metals. Therefore, the melting point of the cladding is the determining factor in high-temperature uses. Pure copper melts at about 1980°F; 95 per cent copper, 5 per cent zinc at 1950°F; 90 per cent copper, 10 per cent zinc at 1910°F; 80-20 copper-nickel at 2190°F; and 70-30 copper-nickel at 2250°F, etc.

### COEFFICIENT OF EXPANSION

Data are not readily available on the coefficient of expansion of copper- or copper-alloy-clad steel strip, although the average coefficient of 30 and 40 per cent copper-clad steel wire is given as 0.0000072 in. per inch per degree Fahrenheit. Inasmuch as the coefficient of expansion for copper is usually quoted as 0.0000098 and, for steel, 0.0000067, it appears that the weighted-sum method, so useful in determining other properties of clad metals, is not strictly applicable. However, if the modulus of elasticity of each component is considered, along with the coefficient of expansion and cross-sectional area or volume of each metal, use may be made of the following formula: \*

$$K = \frac{AcEcKc + AsEsKs}{AcEc + AsEs} \quad (10-1)$$

in which  $A$  = cross-sectional area or volume

$E$  = modulus of elasticity

$K$  = coefficient of expansion

$c$  = copper

$s$  = steel

\* Suggested by L. C. Whitney, Chief Metallurgist, Copperweld Steel Co.

The value of  $K$ , the coefficient of the composite, can be calculated with a fair degree of accuracy. For example, if a clad consisting of 10 per cent (by thickness) of copper on each side of steel is considered, substituting proper values in a sample 1 in. square and 0.1000 in. thick, we have

$$K = \frac{\left\{ \begin{array}{l} 0.020 \times 16,000,000 \times 0.0000098 \\ + 0.080 \times 29,000,000 \times 0.0000067 \end{array} \right\}}{0.020 \times 16,000,000 + 0.080 \times 29,000,000} = 0.0000071$$

Generally speaking, however, and except for very exact work, the coefficient of expansion of the preponderant metal might very well be used on clads with relatively thin coatings. Tests on a sample of straight chrome stainless-steel, clad on both sides with 10 per cent of copper, showed that the expansion rate was about the same as for a solid straight chrome stainless, unclad. The coefficients of clads with thicker coatings, which would exert a more noticeable effect, should be calculated using the preceding formula.

Double clads, with an equal thickness of copper on each side, do not warp or bend when heat is applied. Single clads with 10 per cent of copper by thickness do not warp noticeably on heating, although thicker claddings bow considerably. As a matter of interest, a strip sample composed of 10 per cent copper, 80 per cent steel, 10 per cent stainless warped when heated but straightened out again on cooling.

#### DENSITY

For all practical purposes, the weighted sum of densities of the components can be used as the density of the complete clad metal. For example: If the density of steel is used as 0.284 pci, and that of copper as 0.322, the density of a 10-10 copper-clad steel would be  $(0.20 \times 0.322) + (0.80 \times 0.284) = 0.2916$ . This form of calculation may be used for any type or kind of clad metal.

#### FABRICATING

The hot-rolling characteristics of copper- and copper-alloy-clad metals have been discussed to some extent. It is important to remember that all rolling or working must be done at some temperature below the melting point of the cladding metal. For those metals and alloys with melting points of 1900°F or above, hot working is usually carried out at about 1750 to 1800°F, or about 100 to 150°F below the melting point. This rule applies to the cupronickels, likewise.

Cold working, as rolling or drawing to strip or wire, usually follows the same routine as would be used on unclad steel of the same analysis

of the core of the clad metal. The cold fabricating of copper clads presents no difficulties—punching, shearing, forming, drawing, spinning, and all methods of press work are carried out in a manner again similar to that used on the corresponding steel.

Annealing may be batch or continuous. If bright-annealed clad is desired, the furnace atmospheres that produce bright work on the solid nonferrous metal will likewise produce bright clads. An ordinary 6–1 cracked-natural-gas atmosphere, in a batch-type furnace, will produce bright-copper- or commercial “bronze”-clad steels. Temperature and time cycles are governed by the steel, not the cladding layer.

Pickling is simple. Ordinary dilute sulfuric acid, such as is used for cleaning low-carbon steel will satisfactorily pickle copper clads. The special brightening solutions commonly used on copper and copper alloys can be applied to the clads.

#### GENERAL

In summary, copper- and copper-alloy-clad metals have better corrosion resistance than similar plated metals because of the normally greater thickness of coating and the lack of porosity inherent in clad-metal facings. They are not generally considered so competitive with other coated metals, such as galvanized, aluminized, or tin-plated, for each type possesses certain attributes which make it superior for certain uses.

Clad metals possess greater strength than similar solid nonferrous metals. They present a combination of properties, both physical and chemical, which cannot be obtained with any ordinary solid metal. Additionally, there is an indication that the economies possible in the use of these clad metals will expand their use considerably. Although at present they are being used to a limited degree, mostly for special applications, when cost or scarcity of nonferrous materials becomes more of a factor than it is now, the demand for clad metals should expand considerably.



## CHAPTER 11

# Nickel-Clad, Monel-Clad, and Inconel-Clad Steel

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A clad steel is a composite plate made up of a carbon- or alloy-steel plate to one or both surfaces of which there has been uniformly and inseparably bonded a cladding of some other metal, usually employed for its corrosion resistance.

The development of clad steels was the outcome of a desire to provide economical corrosion-resistant materials, in place of the solid metals of similar analyses, that could be used in the fabrication of large vessels, tanks, agitators, towers, heat exchangers, and other operating and storage equipment at a lower cost. The first of these new bimetals was nickel-clad steel, developed in 1930 by the combined efforts of Lukens Steel Company and The International Nickel Company. Today nickel-clad, Inconel-clad, and Monel-clad steels as well as stainless-clad steels are all manufactured.

The nominal composition of nickel, Monel, and Inconel used as the cladding metal is shown in Table 11-1.

TABLE 11-1. NOMINAL COMPOSITION OF NICKEL, MONEL, AND INCONEL USED AS CLADDING METAL, PER CENT

	Nickel	Copper	Chromium	Iron	Manganese	Silicon	Carbon
Nickel	99.4	0.1	....	0.15	0.2	0.05	0.1
Monel	67.0	30.0	....	1.4	1.0	0.1	0.15
Inconel	78.5	0.2	14.0	6.5	0.25	0.25	0.08

### SELECTION OF CLAD STEELS

Choice of cladding material and thickness of cladding depend on the service conditions under which the vessel is to operate. The factors

governing corrosion are complex. One factor, galvanic corrosion, may be produced when dissimilar materials are in contact in a corrosive solution. Accessory parts such as agitators, coils, and fittings in contact with the corrosive solution should be preferably of the same material as the cladding. Special care should be taken to avoid the use of accessories of less noble materials, as galvanic action may occur and the corrosion of the accessory part may be comparatively rapid.

Occasionally there are applications, such as for salt baths and melting pots, where carbon steel is superior to the more expensive cladding metal with respect to the corrosive media on one side of the plate while the cladding is better able to resist corrosion or oxidation on the other side of the plate.

In general, the factors affecting corrosion are the nature, purity, and concentration of corrosive media, temperature, degree of aeration, rate of flow or movement, pressure, and galvanic effects of dissimilar metals.

#### APPLICATIONS OF CLADDING METALS

*Nickel* is resistant to corrosion by alkaline materials such as caustic soda and caustic potash; nonoxidizing alkaline salts such as chlorides, carbonates, sulfates, sulfides, nitrates and acetates; and acid salts, especially ammonium and zinc chlorides. It is not greatly affected by alkaline peroxide as used for textile bleaching and is satisfactory for handling certain mildly acid products, as in the manufacture of sulfonated oils and organic chloride compounds. Nickel possesses good resistance to fatty acids, particularly from atmospheric temperatures up to distillation temperatures, and is resistant to attack under conditions where organic acids are encountered in processing foods and beverages, being nontoxic, nondestructive to vitamins, and not detrimental to color or flavor. Nickel is also quite resistant to oxidation at elevated temperatures up to approximately 1600°F. In some applications both nickel- and Monel-clad steels are equally suitable. Oxidizing acids, and oxidizing acid or alkaline salts may be quite corrosive to nickel, and it is not recommended for such applications.

*Monel* combines several of the desirable features of both nickel and copper. Under reducing conditions, as in warm unaerated acids, Monel is generally superior to nickel, whereas, under oxidizing conditions, as in aerated acid, alkalies, or salt solutions, it is superior to copper. As a cladding material, Monel is used instead of nickel in special equipment for processing salt, in chlorination reactions with small amounts

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of moisture, in resisting attack by petroleum and vapors containing small amounts of hydrochloric acid, and for marine condensers. Monel possesses good resistance to corrosion by hydrofluoric acid and common organic acids.

*Inconel* is almost completely resistant to corrosion by food products, fruit juices, vegetable oils, fatty acids, meat, dairy products, pharmaceuticals, biologicals, and dilute organic acids. It is also resistant to corrosion by chlorides, particularly magnesium chloride. Inconel is superior to nickel and Monel in its resistance to oxidizing acid salts, such as chromates, dichromates, permanganates, nitrates, and copper sulfate, although not resistant to ferric, cupric, or mercuric chlorides. Inconel resists oxidation and scaling in air and furnace atmosphere at temperatures up to 2000°F.

### CLAD STEEL EQUIPMENT IN INDUSTRY

**Chemical Production.** Nickel-clad steel is extensively used in equipment for the manufacture and transportation of caustic soda and alkalis and also in equipment for processing materials containing caustic. It is commonly used in evaporators, heat exchangers, heaters, filter bodies, tanks for many purposes, tank cars, flakers, and special equipment of L nickel-clad (0.02 carbon, max.) steel for processing caustic of high concentration at elevated temperatures. Nickel- and Monel-clad steels are used in salt manufacturing equipment such as dryers, grainers, tanks, and crystallizers. Clad steel plates have been widely used in the fabrication of stills, evaporators, and autoclaves, particularly if the equipment is large or designed for pressure or vacuum.

**Petroleum.** Applications for use of clad steels in the petroleum field include Monel- and Inconel-clad processing equipment, nickel-clad steel isomerization units, preheaters, heat exchangers, and chlorination equipment. Monel-clad steel is of interest in connection with equipment for handling hydrofluoric acid.

**Rubber, Natural and Synthetic.** Clad steel applications in this field include coagulators, mixers, and processing tanks for production of butadiene; alkylators, scrubbers, and saturators for the production of styrene; Inconel-clad steel latex emulsion and impregnating tanks and caustic tanks in the Thiokol process; agers for rubber-covered rolls; and processing tanks and filters for reclaiming rubber from scrap.

**Metal Heat Treatment and Melting.** Clad steel applications in this field include fused-salt baths and chloride baths of Inconel-clad steel, and nitrite and nitrate baths of L nickel-clad steel.

**Pulp and Paper Manufacture.** Outstanding applications for clad steels in this field include nickel-clad steel head and flow boxes, caustic evaporators and tanks, high-pressure digesters for wood fiber, cylinder mold vats, screen housings and vats, and mixers for paper-sizing materials.

**Resins, Plastics and Varnish.** Both nickel- and Inconel-clad steels have been used for resin-reaction equipment and oil-bodying kettles. Inconel-clad steel processing kettles have given good service when used for production of wood-oil substitutes. Varnish kettles, both portable and set kettles, of nickel-clad steel, as well as rebottoms for existing kettles, have also been satisfactory. Nickel-clad steel equipment for the production, storage, and transportation of phenol is commonly used. L nickel-clad steel is used for fused-caustic applications in connection with the synthetic manufacture of phenol. Inconel-clad steel is suitable for storage equipment for formaldehyde. Nickel-clad steel is commonly used in the production of ethyl cellulose, ethyl chloride tanks, and alkylation autoclaves.

**Soap, Oils, Fatty Acids, and Glycerine.** Nickel-clad steel soap kettles, top sections and covers, crutchers, salt-lye filters, hoppers, and caustic tanks are common applications. Inconel-clad steel is an excellent choice of material for high-pressure saponification equipment. Clad steel applications in processing oil and fat include black-stock wash tanks, Twitchell process tanks, and fatty-acid storage tanks for service below distillation temperatures. In glycerine production, evaporator bodies, salt catchers, filters, and bleaching tanks of nickel-clad steel give satisfactory service.

**Pharmaceutical.** Clad steels used in pharmaceutical processing include Inconel-clad steel distillation equipment; glandular extractors and evaporators for pectin, liver, and meat extracts; ingredients for tonics; and nickel-clad steel sterilizers, disinfectors, dryers, mixers, table tops and working surfaces.

**Food Processing.** Clad steel food-processing equipment includes nickel-clad steel evaporators and crystallizers for glucose; Inconel-clad steel bleaching tanks; cookers of nickel- and Inconel-clad steel for dextrine, cereal, preserves, jellies and meat products. Other applications are mixers, brine tanks, frozen-food and sea-food processing equipment of nickel-clad; cooking tanks and evaporators of Inconel-clad steel for tomato products.

**Degreasing Equipment.** Nickel-clad steel is suitable for degreasing equipment in which chlorinated, petroleum, or coal-tar solvents as well as alkaline degreasing solutions are used.

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**Textile.** Clad steel applications in the textile field include yarn-conditioning ovens, size kettles, and peroxide bleaching keirs as well as Inconel-clad steel dyeing keirs and tanks.

**Hydraulics.** Clad steel applications in the hydraulic field include nickel-clad steel penstocks, expansion joints, Venturi section, weirs, dam-gate face plates and guides.

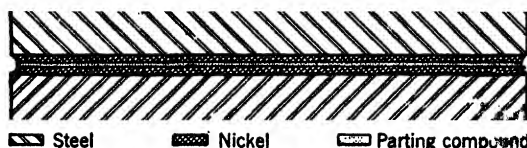


FIG. 11-1. Section Showing Arrangement of Metals before Rolling Nickel-Clad Plates.

### MANUFACTURE

In making nickel-, Monel-, and Inconel-clad steels, a heavy slab of steel of the desired mechanical properties is thoroughly cleaned on one of its flat surfaces. A plate of cladding material, with one surface specially prepared, is placed on the steel slab with the prepared surfaces

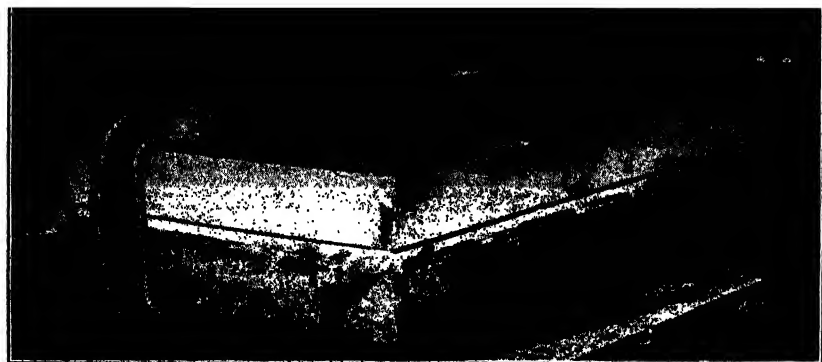


FIG. 11-2. The Completed Sandwich, Ready for Continuous Welding.

in contact and is secured in place by welds and bars. A second similarly prepared slab of steel and cladding material is placed on top of the first one with the clad surfaces facing and with an infusible compound between, Fig. 11-1. This makes a four-layer slab, or "sandwich," which is held together and sealed from all contamination by continuous welding on all edges, Fig. 11-2. This assembly is heated

in a soaking pit to a temperature of 2250–2300°F, then rolled on Lukens 206-in. Mill. As the rolling reduces the thickness, it permanently bonds the cladding to the steel. The edges of the rolled assembly

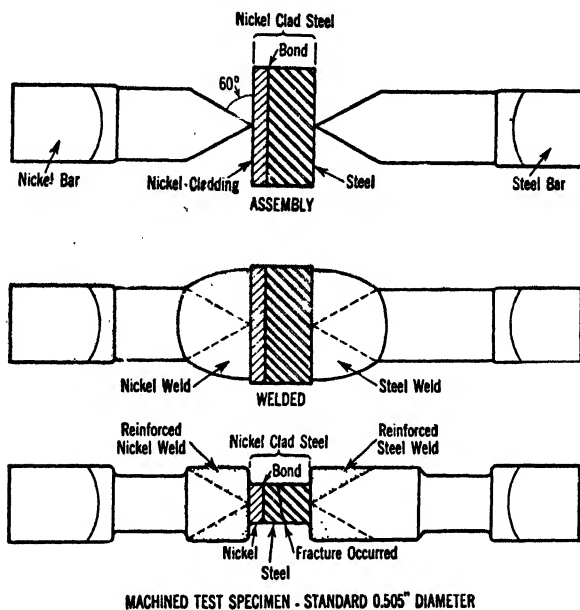


FIG. 11-3. Physical Test of Nickel-to-Steel Bond. Fracture occurred in steel-plate portion at 55,500 psi.

are cut off, and two component parts of the "sandwich" are separated yielding two clad steel plates.

The efficiency of this rolled bond is demonstrated by a test which was devised to yield a quantitative value of its strength, Fig. 11-3. The



FIG. 11-4. Twist Test to Demonstrate Permanence of Bond.

specimen broke in the steel plate at 55,000 psi to prove the greater strength of the bond; that is, the failure of the composite plate in the steel portion demonstrates that the strength of the nonferrous metal to steel bond is stronger than the steel itself. Tests have proved that the bond has a minimum shear strength of 20,000 psi. The conventional

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twist test, Fig. 11-4, is further evidence of the permanence of the bond between clad and base metal.

### MECHANICAL PROPERTIES

The corrosion-resistant metal used as the cladding is homogeneous and dense in structure and is the same chemically and physically as solid nickel, Inconel, or Monel. Table 11-2 gives physical constants and mechanical properties of these corrosion-resistant high-nickel alloys compared to mild steel (SAE 1020).

TABLE 11-2

	Nickel	Monel	Inconel	SAE 1020
Density, pci	0.321	0.319	0.307	0.284
Specific gravity	8.89	8.84	8.51	7.86
Melting point, °C	1435-1445	1300-1350	1395-1425	1527
°F	2615-2635	2370-2460	2540-2600	2760
Thermal conductivity, cal/sq cm/sec/°C/cm (0-100°C)	0.145	0.062	0.036	0.158
Btu/sq ft/hr/°F/in. (32-212°F)	420	180	104	460
Expansion, thermal, cm/cm/°C (25-100°C)	0.0000133	0.0000140	0.0000115	0.0000119
in./in./°F (77-212°F)	0.0000072	0.0000078	0.0000064	0.0000066
Moduli of elasticity, tension	30,000,000	26,000,000	31,000,000	30,000,000
torsion	11,000,000	9,500,000	11,000,000	12,000,000
Poisson's ratio	0.31	0.32	0.29	0.28
Magnetic transformation temperature, °C	360	43-60	Below -40	768
°F	680	110-140	Below -40	1415
Avg. mechanical properties hot-rolled plate				
Yield strength, 0.20% offset, 1000 psi	25	50	60	35
Tensile strength, 1000 psi	75	90	100	60
Elongation in 2 in., %	40	35	35	35
Brinell hardness, 3000 kg	110	150	180	125
Impact Charpy room temp., ft-lb	195	219	236	25
Impact Charpy temp. -112°F, ft-lb	236	213	206	.....

The base metal is generally of carbon steel but may be any low-alloy steel of flange or firebox quality or similar steels, conforming to ASTM, ASME, or other standard steel specifications. If special compositions are required for alloy steels for which no ASTM specification

TABLE 11-3

ASTM Specification	Tensile Strength, psi	Yield Point, Min. psi	Elongation in 8" Min. %	Elongation in 2" Min. %	Carbon, Max. % Plate to 2"	Mn, Max. %	P, Max. %	S, Max. %	Si	Ni	Mo	Va
Grade B, A285 firebox	50,000 to 60,000	0.5 T.S. Min. 27,000	1,550,000 Tens. str.		0.22	0.80	0.035	0.04	.....			
Grade B, A201 firebox	60,000 to 70,000	0.5 T.S.	1,550,000 Tens. str.	1,750,000 Tens. str.	0.27	0.80	0.035	0.04	0.15 to 0.30			
Grade B, A212 firebox	70,000 to 82,000	0.5 T.S.	1,600,000 Tens. str.	1,750,000 Tens. str.	0.33	0.90	0.035	0.04	0.15 to 0.30			
Grade B, A203 firebox	70,000 to 82,000	0.55 T.S. Min. 40,000	1,650,000 Tens. str.	1,750,000 Tens. str.	0.20	0.80	0.035	0.04	0.15 to 0.30	2.0 to 2.75		
Grade B, A204 firebox	70,000 to 82,000	0.55 T.S. Min. 40,000	1,650,000 Tens. str.	1,750,000 Tens. str.	0.23	0.90	0.035	0.04	0.15 to 0.30		0.40 to 0.60	
Grade B, A225 firebox	75,000 to 87,000	0.55 T.S. Min. 43,000	1,650,000 Tens. str.	1,750,000 Tens. str.	0.20	1.45	0.035	0.04	0.15 to 0.30			0.08 to 0.14

Refer to above specifications for heavier gages.



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is available, agreement may be reached between the purchaser and the manufacturer. The values in Table 11-3 are based on minimum mechanical properties and chemical requirement of the ASTM steel specifications that are in general use for backing of the corrosion-resistant cladding. The physical properties of the composite plate, as determined by tensile tests, are equal to or better than the minimum requirements of the specifications for the base steel plate used.

A vessel made of clad steel can take advantage of high- or low-temperature properties of special steels such as molybdenum or nickel steels when used in backing plate steels.

Substantial cost reduction in material, fabrication, and freight can be made by using a backing material of higher allowable stress.

### CLAD THICKNESS

The clad thickness is normally specified as a percentage of the total thickness of the composite plate. The most common thicknesses are 10 and 20 per cent, but they may also vary from 5 to as much as 50 per cent, or the cladding thickness may be specified, such as 0.050 in., regardless of the composite plate gage. The type and thickness of the cladding are determined by the special requirements of each application. Where necessary, both sides may be clad, as in the case of vessels with partitions. The thickness of the cladding will be uniform throughout the plate area and held to close tolerance whatever amount in percentage or gage is specified by the designer. Owing to the sandwich method of assembly and the high and uniform rolling pressure used, the cladding thickness is consistent. This evenly proportioned layer of cladding is advantageous when fabricating.

Uniformity of cladding thickness is essential in the welding of clad steels as a considerable variation in the amount of alloy metal may seriously affect the quality of the weld. The process of manufacture of the clad steel must be controlled to maintain the variation in cladding in percentage of the total composite plate gage. The ordered gage of  $\frac{1}{4}$  in. including 10 per cent clad ranges from 10 to 12 per cent only or from 0.025 to 0.030 in. Thus the user will be assured of the cladding thickness he specified, and the fabricator can maintain a definite amount of steel in the lip for safe fit and cladding. All types of stainless clad steel \* are made by this same process.

\* See Chapter 12.

Clad steel plates have a silver-grey matte finish on the clad side, and the steel surface is that of a typical hot-rolled steel plate.

## FORMED HEADS AND FITTINGS

Standard types of heads, including flanged-only heads, standard flanged and dished heads, flanged and dished ASME Code and API-

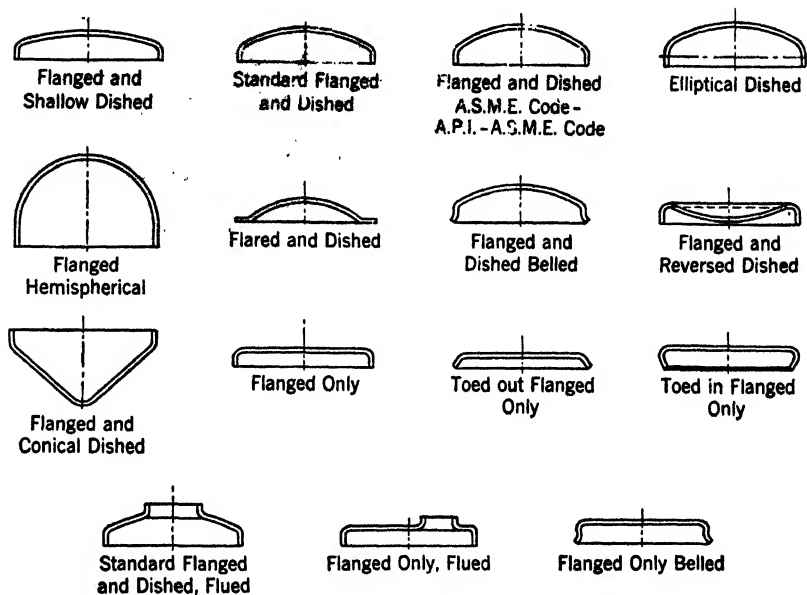


FIG. 11-5. Examples of Several Styles of Formed Heads.

ASME Code heads, elliptically dished heads and other styles; flued openings and flared ring sections for manholes and hand holes; flanges; in fact, practically any formed shape can be made in clad steels. Examples of some styles of heads are shown in Fig. 11-5. The materials respond readily to hot spinning and hot and cold pressing. Circles for cold pressing should be specified as "annealed." Pressed tank manhole flanges made for storage tanks may be used to advantage with flared and dished covers for low-pressure vessels. Forged and tapped welding flanges, Vanstoned ends, seamless tubing and standard IPS pipe, castings and other accessories required in the construction of tank and plate work may be procured in solid nickel, Inconel, and Monel.

## DESIGN

The designing of equipment of clad steels follows that for similar equipment in commercial steel. The thermal coefficients of expansion of nickel, Inconel, Monel, and steel are approximately the same within

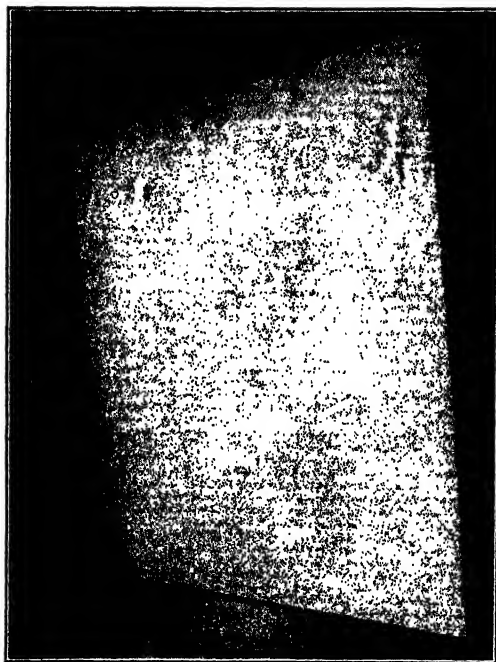


FIG. 11-6. Wide Plate of 10 per cent Nickel-Clad Steel,  $\frac{3}{4}$  in. Thick, Measuring 152 in. in Length, 151 in. in Width, and Weighing 5315 lb.

the range in which these clad metals are normally used. Maximum heat-transfer efficiency is provided by the uniform thickness of the cladding and permanence of the complete bond. Table 11-2 gives coefficients of thermal expansion and conductivity for nickel, Monel, Inconel, and SAE 1020 steel. As shown in this table, the similarity in the high heat-transfer values for nickel and steel offers design advantages in this respect.

The economic design of equipment is also aided by the availability of large plates and heads. Plates of nickel-clad, Inconel-clad and Monel-clad steels up to 178 in. wide and in thickness from  $\frac{3}{16}$  in. to over 3 in. are produced.

By minimizing the number of operations, such as trimming, bending, forming, edge preparation, and welding of additional seams, ordinarily required when several narrow plates are joined, wide plates reduce fabricating costs. They also make it possible to increase the rate of shop production without increase in plant area or equipment. In fact, in all applications involving clad steel plates, the widest plates available can always be employed with resulting savings in fabrication

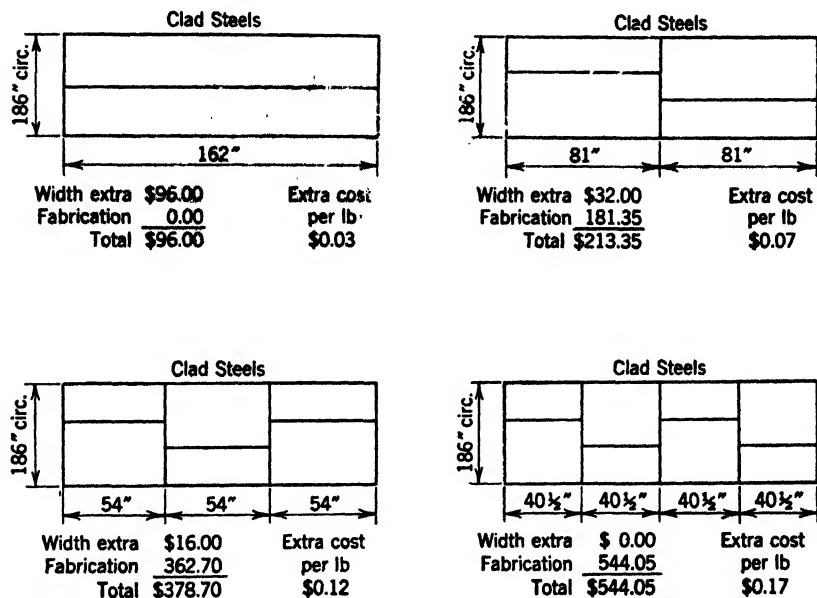


FIG. 11-7. Example of Use of Economical Plate Sizes.

costs. Many shells can be made from a single plate of the dimensions shown in Fig. 11-6, which is a 10 per cent nickel-clad steel plate 152 in.  $\times$  151 in.  $\times$   $\frac{3}{4}$  in. thick.

A typical example of the use of economical plate sizes for the construction of pressure vessels and tanks is illustrated in Fig. 11-7. The number of plates or courses selected affects the cost of construction and may result in a saving almost equal to the base price of the clad steel plate itself. The figures show that the proper selection of plate sizes can make the difference of \$0.03 to \$0.17 a pound, or a saving of \$0.14 a pound, in fabricating cost.

Studies have been conducted over a period of several years toward determining the average cost that would represent a cross section of the fabricating industry. These costs have been compared to width

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extra on an extra cost per pound base and are shown in Fig. 11-8. For example, with a  $\frac{1}{2}$ -in.-gage plate fabricated in accordance with U-68 requirements at \$11.80 per foot, the extra fabricating cost using two

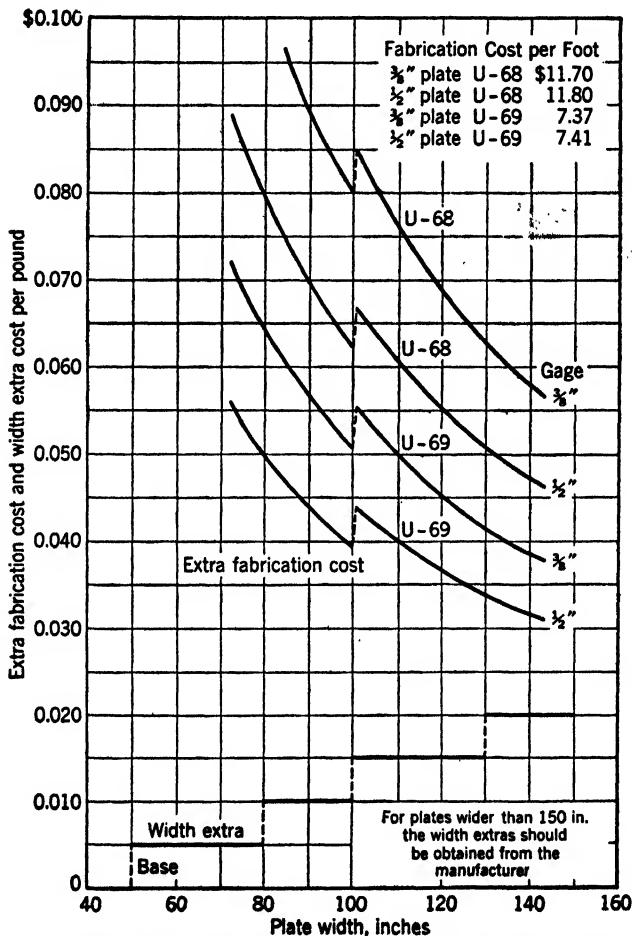


FIG. 11-8. Plate Width versus Extra Fabrication Cost and Width Extra.

42-in. plates to make up an 84-in. plate by welding would cost \$0.075 per pound; a single plate 84 in. wide would cost \$0.010 per pound in width extras. This results in a saving of \$0.065 per pound or almost half of the base price of the material, in addition to the other advantages of time and man-hours. As a further illustration, a single plate 108 in. wide would have a width extra cost of \$0.015 per pound, and

the fabricating cost to join two 54-in. plates of  $\frac{1}{2}$ -in. gage and built by U-69 construction would cost almost \$0.042 per pound. The saving by using the single wide plate would be \$0.027 per pound. It should be noted that the width extras are low in proportion to the base price of the material and the fabricating costs for clad steels.

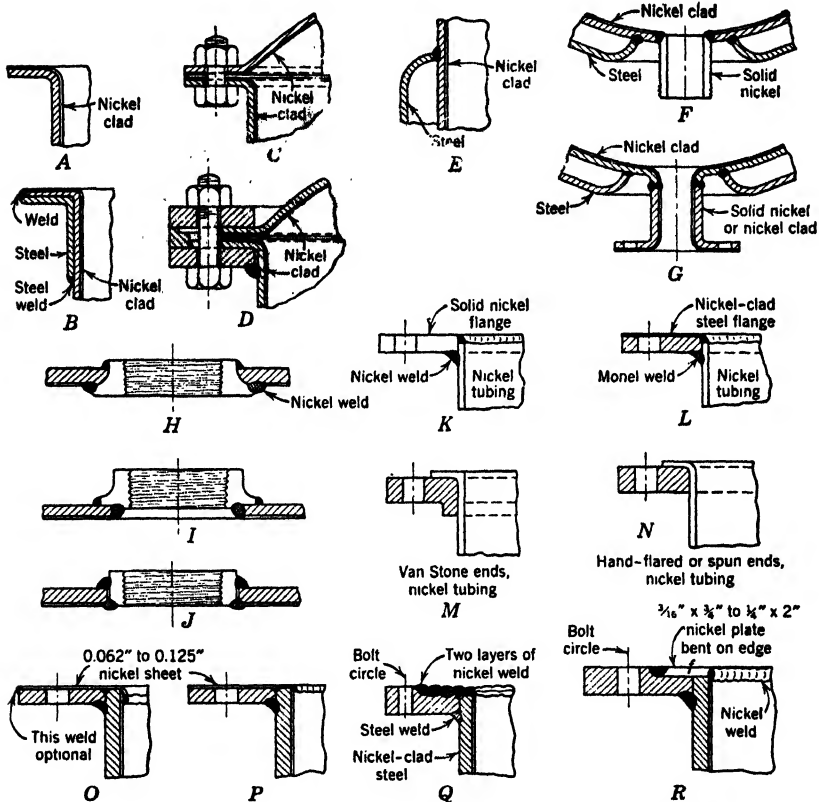


FIG. 11-9. Methods of Construction to Provide Continuity of Cladding Surfaces.

In designing a clad vessel to meet the ASME Code for unfired pressure vessels (case 896, reopened December 29, 1947), it is permissible to use the full thickness of the composite plate in design calculations.

The maintenance of a continuous surface of the cladding material is the only problem new in the design of pressure vessels and other types of equipment. Figure 11-9 shows a number of methods of construc-

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tion which provide continuity of the cladding surface at joints, top reinforcing curbs, flanges, outlets and fittings.

### FABRICATION

The many types and sizes of vessels which have been fabricated from clad steel plates indicate that this work can be done in any commercial shop employing reasonable care and supervision in the fabrication of any of its products.

### CARE IN HANDLING

Clad steels are carefully inspected and protected at the mill before shipment. Similarly, to avoid subsequent damage to the surface of the cladding, caution should be exercised in handling during fabrication. Bending rolls, dies, and tools regularly used for steel can be adapted for the clad materials, also, but they should be wiped or brushed clean of loose scale and steel particles that otherwise might become imbedded in the clad surface. It is advisable to cover the bending roll with paper to prevent contact with the clad surface.

Plates should not be dragged across a clad surface as this might damage or gouge the cladding enough to expose the base steel plate. Carelessly dropped chisels or other sharp tools could have the same effect. Center punch marks on the clad surface should be avoided.

Whenever possible, clad steel plates should be handled around the shop and at the shears and punches with the clad side up to prevent gouging and scratching of the clad surface.

In order to avoid contamination of the clad surface with shop dirt, a protective paper covering may be pasted to the clad surface. The paper coating may be left in place until fabrication has been completed. Of course, prior to welding, it will be necessary to remove about 1 in. of the paper along the edges to be welded.

Sulfur or lead bearing compounds such as marking paints or crayon and drawing oils should be removed from the clad surface to prevent embrittlement of the clad surface prior to heat treatment or service.

### COLD WORKING

Cold operations such as bending, flanging, forming, shearing, and the like are performed on clad steel in the same manner as in commercial steel plate work. No change in equipment or provision for

special tools, except for suggestions already indicated under "Care in Handling," should be necessary. Shearing and punching are best accomplished in such a way as to throw the burr on the steel side.

Severe cold operations, such as pressing and die work, generally require annealed plate. "Cold-pressing grade steel" should be specified as the base plate for clad steels where severe cold work is to be done.

Proper treatment to condition the plates for severe cold work is accomplished by heating to 1500–1600°F for nickel-clad, 1600–1700°F for Monel-clad, and 1700–1800°F for Inconel-clad steels. In each case the material should be withdrawn as soon as it has reached furnace temperature and allowed to cool in the air.

### HOT WORKING

The hot forming of clad steels is performed in the same way as that of carbon steel. Here again care must be taken to avoid gouging or otherwise marking the clad surface, and dies should be dressed to remove burrs which might cause damage. The fuel must contain less than 0.5 sulfur for the heating of clad steels. The nickel-, Inconel-, and Monel-clad steels should be heated outside the combustion zone in a reducing atmosphere. The plate, with the clad side up, should be supported on clean steel rails or clean firebrick to keep the nickel from contact with slag and cinder on the furnace bottom that might cause damage through embrittlement.

Fuels high in sulfur, such as coal, coke, unwashed producer gas, crude oil and others having sulfur content in excess of 0.5 per cent may destroy the ductility of the cladding metal through embrittlement and should not be used. Satisfactory fuels for heating clad steels are those having less than 0.5 per cent sulfur, such as natural gas, butane, propane, gasoline, kerosene, or fuel oil purchased to specification. When combustion and fuel conditions are questionable, or where a long heating time may be required for heavy plate, a lime wash or similar protective material applied to the surface may often prevent damage.

The proper length of time to heat a clad steel plate is the minimum required to heat the piece uniformly; to minimize the time, the pieces should be charged into a hot furnace. It is undesirable to expose the clad material to combustion gases in the heating furnace once the plate has reached the required temperature. The best hot-working range for clad steels is as follows: Monel 1850 to 2150°F, nickel and Inconel 1900 to 2250°F.



## FLAME CUTTING

Clad steel plates of  $\frac{1}{4}$ -in. gage and heavier having a cladding not greater than 20 per cent of the total thickness may be flame-cut almost as readily and at about the same speed as carbon-steel plate. The cut is made from the steel side by inclining the torch about  $10^\circ$ , with the tip pointing toward the completed part of the cut. A tip one size larger than for steel should be used, with about the same oxygen pressure. On plates thinner than  $\frac{1}{2}$  in., it is preferable to chip through the cladding to the steel along the line of cut and flame-cut from the clad side through this chipped groove.

## METAL-ARC WELDING

The service performance of welds in nickel-, Monel- or Inconel-clad steel equipment has demonstrated in a practical manner that properly made welds possess good corrosion resistance, ductility and strength.

An important requirement in building clad steel equipment is that no steel should be exposed and that a continuous surface of the cladding metal must be maintained. This is readily accomplished in welded butt and lap joints, since nickel or nickel-alloy weld metal is deposited over the steel weld or plate at the joints. However, with manholes, flanges, gasket surfaces, and the like, a sheet covering or layer of nickel, Monel, or Inconel weld metal over the steel is necessary as shown in Fig. 11-9. When more than one layer is necessary to obtain the desired thickness of deposit, each succeeding layer should be laid down by "weaving" to produce bends up to  $\frac{3}{8}$  in. wide. Several thin layers are preferred to a smaller number of thick layers in order to minimize dilution of the weld with base metal. Heavier electrodes,  $\frac{3}{16}$  in. or  $\frac{1}{4}$  in. in diameter, may be used for heavy overlays after the first  $\frac{1}{8}$ -in. overlay has been deposited with  $\frac{1}{8}$ -in.- or  $\frac{5}{32}$ -in.-diameter electrodes.

The edges of the composite plates are beveled for welding by machining in the usual manner and with the same tools employed for carbon steel.

The abutting edges should fit together with the same accuracy required for any quality workmanship, such as specified by the various code requirements. In fact, the offset between the meeting edges should not be greater than the thickness of the cladding, closer if possible.

The code requirements stipulate that such alignment tolerances must be held; and they should be maintained not only for appearance, but also to prevent the pickup of the clad metal in the deposition of the first steel bead.

Owing to the uniformity of the cladding thickness produced by the "sandwich" method, the alignment of abutting edges will produce a

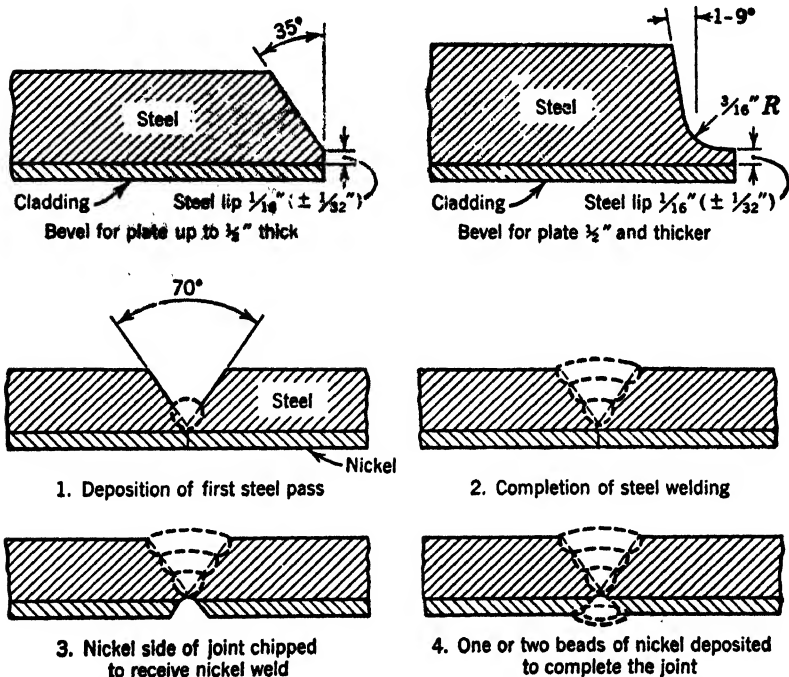


FIG. 11-10. Welding Sequence for Nickel-Clad Steel. The same sequence is followed for welding Monel-clad and Inconel-clad steel plate but Monel and Inconel electrodes, respectively, are used for welding the clad side.

joint that will reduce any danger of alloy pickup if the bevels and lips have been machined correctly. Although the fit-up requirements are no more stringent than those for ordinary steel, carelessness in fit-up should be avoided at all times whether limitations are imposed or not.

One of the most important changes necessary to the welding of most clad steels must be taken into account at this point because of possible metallurgical reactions, namely: The bevel on the steel side should not include the cladding surface. In fact, a square land of not less than  $\frac{1}{16}$  in. should be left in the lip above the clad metal as shown in Fig.

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11-10. While the steel side is welded first with a commercial steel electrode and then the clad side with the appropriate nickel or nickel-alloy welding electrode, the procedure to be followed in the deposition of the first steel bead in the bottom of the groove is extremely important.

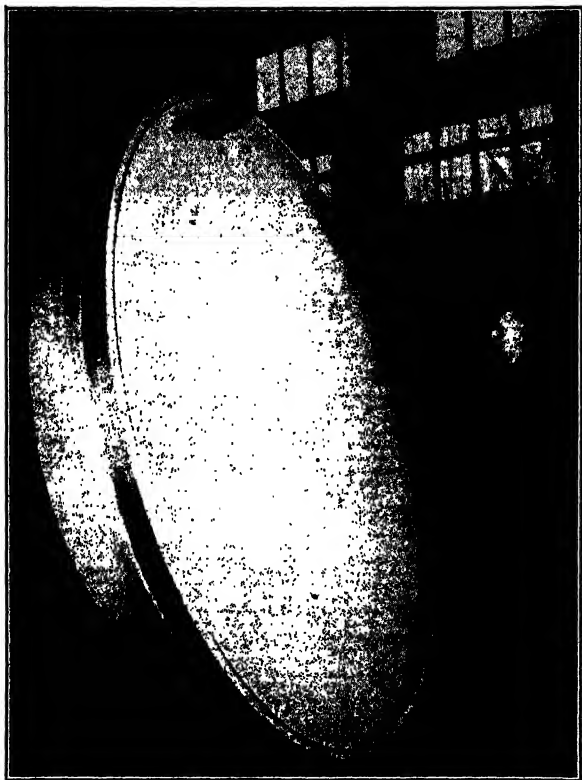


FIG. 11-11. Nickel-Clad Steel Elliptical Dished Head 8 ft 8 in. Outside Diameter Weighing about 6900 lb, for Use in the Fabrication of a 4700-gal Jacketed Autoclave for Chemical Processing.

The first steel bead on the steel side of the groove should be run with the amperage on the low side of the recommended current range in order that the bead should not penetrate and be contaminated with the cladding metal. If the first steel bead absorbs any of the cladding material, an iron alloy is formed in this steel bead producing a martensitic structure of high hardness and low ductility. The first bead may crack, requiring chipping and rewelding, or it may be just hard

enough to lower the ductility of the completed weld to a degree that it will fail to meet the required elongation specifications during the physical testing of the welded coupons.

To repeat, this difficulty is avoided by leaving  $\frac{1}{16}$  in. minimum of steel in addition to the clad thickness of the lip, and by running the first steel bead "cold."

For plates up to  $\frac{1}{2}$  in. thick, inclusive, a V groove with a  $70^\circ$  included angle is preferred; whereas for plates  $\frac{3}{4}$  in. and thicker the U groove should be used. Clad steel heads are beveled in a like manner to plates as illustrated in Fig. 11-11.

The first steel bead is deposited in the bottom of the groove with the same care as in welding of regular-quality steel, with the additional precaution that penetration should be carefully controlled. As in any ordinary steel, each bead is brushed to remove welding slag, and the succeeding beads are deposited to fill the groove.

Care must be exercised, when chipping the clad side, to remove all steel welding slag and the unfused lip. The groove should be opened or tapered on the sides, to provide adequate room for manipulation of the welding electrode. The depth of the groove should be kept to a minimum but must, at all times, show sound steel weld metal.

In the welding of plates up to  $1\frac{1}{4}$  in. thick, the steel side may be completely welded before the clad side is chipped and welded. However, for plates heavier than  $1\frac{1}{4}$  in. it is at times helpful to fill the steel groove only partly, then chip and weld the clad side, and finally complete the steel side of the joint. This practice reduces the amount of warping and overcomes the tendency to crack as a result of the extension of the unfused area in the form of a stress crack-up through the steel bead.

Although other methods of welding, such as oxyacetylene, carbon-arc and atomic-hydrogen, may be used for the welding of clad metals, the preferable method and the one most commonly used is the metal arc. D-c reversed polarity is used with electrodes *a*, *b* (listed below), whereas either alternating or direct current may be used with electrodes *c* and *d* when the clad side is welded.

For welding the clad side the recommended electrodes for the corresponding cladding materials are:

- (a) 131 nickel welding electrode.
- (b) 130X Monel welding electrode.
- (c) 133 80% nickel, 20% chromium welding electrode (for welding Inconel-clad).

## 446 Nickel-Clad, Monel-Clad, and Inconel-Clad Steel

Sizes of electrodes and recommended amperages are given in Table 11-4.

TABLE 11-4. ELECTRODE DIAMETERS AND AMPERAGES FOR NICKEL-CLAD, MONEL-CLAD, AND INCONEL-CLAD STEEL

Plate Thickness, in. (Minimum Cladding 10%)	Electrode Diameter, in.	Recommended Current Range, Amperes			
		131	130X	133	133
		d-c	d-c	a-c	d-c
$\frac{3}{16}$ – $\frac{3}{8}$	$\frac{1}{8}$	95–120	60–95	90–110	80–100
$\frac{1}{16}$ and thicker	$\frac{5}{32}$	120–160	80–150	130–150	110–130

The usual practices prevailing in the shop, including size and type of welding rod, current adjustment, and manipulation peculiar to in-

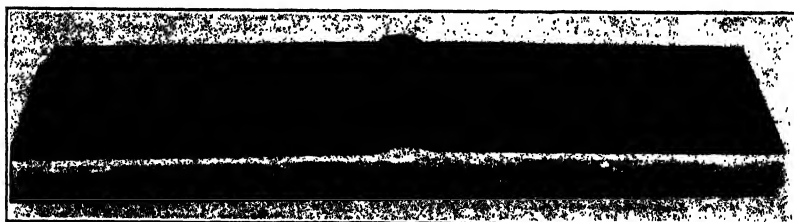


FIG. 11-12. Welded Inconel-Clad Plate.

dividual operators, can be used without important modifications in welding the steel side of the plate. A completely welded clad steel plate is shown in Fig. 11-12.

### MECHANICAL PROPERTIES OF NICKEL-CLAD METAL-ARC WELDS

Test plates  $1\frac{1}{16}$  in. thick and clad 10 per cent, made in accordance with requirements for ASME Class U-68 welds, showed the physical properties listed in Table 11-5. The welded test plate was stress-

TABLE 11-5

	Reduced Section Tensile	Full Section Tensile
Yield strength, psi	40,700	40,300
Tensile strength, psi	65,300	59,800
Elongation, present in 2 in.	25	22

relieved at 1150 to 1200°F, for 45 min at this temperature. The exographs were clear, showing the complete weld to be free of defects.

Standard free bend tests, with the steel weld outside, produced elongation values of 31 per cent in the weld, without failure. Reverse free bend tests, with the nickel weld outside, gave over 30 per cent elongation.

#### STRESS RELIEVING

When stress relieving is required, the usual stress-relieving treatment prescribed for carbon steel is employed for welded clad steel vessels.

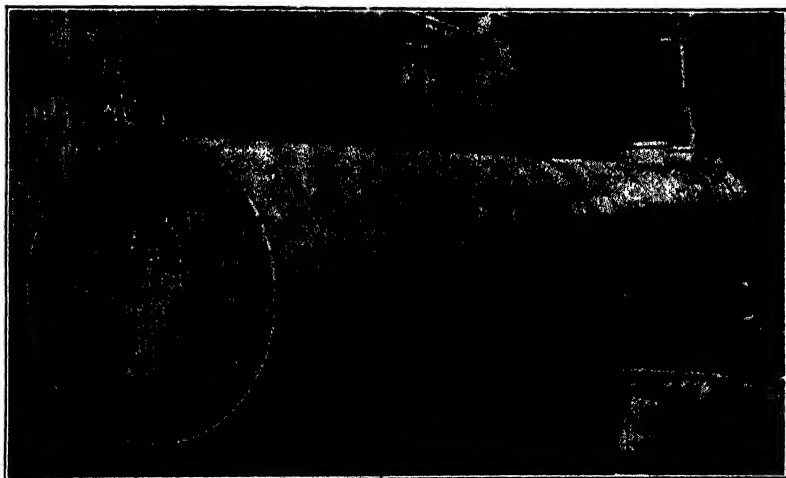


FIG. 11-13. Heat-Exchanger Section 20 ft. Long, Fabricated of Monel-Clad Steel. Photo shows Monel tube bundle being placed in position.

The vessel is heated to 1150 to 1200°F and held at that temperature for 1 hr per inch of the maximum thickness of the composite material. It is allowed to cool in the furnace to 500°F at which it may be removed. For vessels in which varying thickness of material are joined together or where a rigid structure is to be stress-relieved, both heating and cooling should be performed slowly in order to permit uniform expansion and contraction of the vessel and its internals or attachments like the vessel shown in Fig. 11-13.

Sulfur contamination from the fuel must be avoided. Chalk, paint, or other marking materials should be removed from the clad surface before heat treatment.

TABLE 11-6. SPECIFIC DATA ON THE RESISTANCE OF MONEL, NICKEL, AND INCONEL TO CORROSION BY SEVERAL TYPICAL MEDIA \*

Corrosive Medium	Exposure Condition (Concentration of Chemical in % by Weight)	Corrosion Rate					
		Monel		Nickel		Inconel	
		mdd *	ipy †	mdd *	ipy †	mdd *	ipy †
Alkalies	1.1% NH <sub>3</sub> aerated at atmospheric temperature	.....	.....	0	0.000	.....	.....
	2.5% NH <sub>3</sub> aerated at atmospheric temperature	.....	.....	3,275	0.532	.....	.....
	2.7% NH <sub>3</sub> aerated at atmospheric temperature	0	0.000	.....	.....	.....	.....
Ammonium hydroxide	3.6% NH <sub>3</sub> aerated at atmospheric temperature	434	0.070	.....	.....	0	0.000
	5% NH <sub>3</sub> aerated at 86°F	.....	.....	.....	.....	1	0.00017
	10% NH <sub>3</sub> aerated at 86°F	655	0.107	.....	.....	0	0.0000
	15% NH <sub>3</sub> aerated at 86°F	.....	.....	.....	.....	.....	.....
	23% NH <sub>3</sub> aerated at 86°F	224	0.036	.....	.....	.....	.....
Potassium hydroxide	25.8% NH <sub>3</sub> aerated at atmospheric temperature	.....	.....	1,149	0.187	.....	.....
	In 95% solution at 300°F for 6 hr	.....	.....	.....	0.00001	.....	.....
	In evaporator concentrating from 30% to 50% for 16 days	0.4	0.00007	0.07	0.00001	.....	.....
	In evaporator concentrating to 70% for 6 months	1.2	0.0002	0.6	0.0001	.....	.....
	In storage tank for 50% solution at 130° to 165°F	.....	.....	9	0.0015	.....	.....
Sodium hydroxide	In storage tank for 70% solution at 195° to 240°F for 90 days	0.16	0.00003	0.13	0.00002	0.10	0.00002
	In 95% solution at 600°F for 75 hr	7	0.001	0.97	0.0001	2	0.0003
	.....	.....	.....	13	0.002	.....	.....
Atmospheres	On roof in New York City for 6 years	0.3	0.00005	0.9	0.00015	.....	.....
	Near salt water at La Jolla, Calif., for 6 years	0.03	0.000005	0.02	0.000003	.....	.....
	.....	.....	.....	.....	.....	.....	.....
Acids, mineral	0.5% solution, unsaturated, boiling	178	0.029	1,875	0.304	.....	.....
	1% solution saturated with nitrogen at 86°F	20	0.003	7	0.001	.....	.....
	2% solution in apple washer at 80°F to 120°F for 192 hr	442	0.073	451	0.074	453	0.076
	3.6% solution unsaturated at 140°F for 100 hr	220	0.036	547	0.069	.....	.....
	5% solution saturated with nitrogen at 86°F	45	0.007	23	0.004	78	0.013
	5% solution saturated at 86°F	508	0.083	13	0.032	591	0.098
	5% solution saturated with hydrogen at 86°F	.....	.....	.....	.....	78	0.013
	5% solution saturated with nitrogen at 158°F	289	0.047	.....	0.134	.....	.....
	5% solution saturated at 185°F	.....	.....	.....	.....	9,550	1.6
	10% solution unsaturated at 165°F	2,570	0.416	.....	.....	.....	.....
Hydrochloric acid	20% solution saturated with nitrogen at 86°F	459	0.074	268	0.043	.....	.....
	25% solution saturated at atmospheric temperature	1,405	0.23	.....	.....	.....	.....
	30% solution saturated with nitrogen at atmospheric temperature	1,639	0.268	410	0.066	.....	.....
	.....	.....	.....	.....	.....	.....	.....
	.....	.....	.....	.....	.....	.....	.....

\* Nickel and Nickel Alloys, The International Nickel Co., New York.





TABLE 11-6. SPECIFIC DATA ON THE RESISTANCE OF MONEL, NICKEL, AND INCONEL TO CORROSION BY SEVERAL TYPICAL MEDIA \* (Continued)

	Corrosive Medium	Exposure Condition (Concentration of Chemical in % by Weight)	Corrosion Rate					
			Monel		Nickel		Inconel	
			mdd *	ipy †	mdd *	ipy †	mdd *	ipy †
Acids, Organic (Cont.)	Fatty acids	Stearic and Oleic in still at 440°F for 21 days	24	0.004	25	0.004	6	0.001
	Formic acid	{ 90% in storage tank for 14 days	61	0.01	25	0.004	24	0.006
		{ 90% in still at 212°F for 8 days	80	0.013	111	0.018	119	0.02
	Lactic acid	{ 45% aerated at atmospheric temperature	123	0.02	128	0.021	0.8	0.0001
	Oxalic acid	{ Un aerated at atmospheric temperature	48	0.008	47	0.008	0.2	0.00003
Organic Compounds	Tartaric acid	{ 30% un aerated at 140°F	49	0.008	69	0.011	14	0.002
		{ 1.1% un aerated, boiling	4	0.0007	47	0.008	0.0	0.00000
	Beer	{ 57% in evaporator at 130°F	29	0.005	0.13	0.0002	0.09	0.000015
		{ In ale storage tank for 10 weeks	0.06	0.00001	0.11	0.00002		
	Carbon tetrachloride	{ Partially immersed in boiling mixture of carbon tetrachloride and water	15	0.00002				
Ethyl acetate		In esterification still with small amount of sulfuric acid	27	0.004	11	0.0018		
	Formaldehyde	37% in storage container	32	0.005	36	0.006	41	0.007
	Gin	{ 90 proof gin at atmospheric temperature for 2 months	5	0.0009	2	0.003	0.09	0.000015
		{ Cooling from 145°F to 78°F	0.015	0.0000024	0.03	0.000005	0.005	0.0000008
		{ Heating from 50°F to 145°F	79	0.013	250	0.041	1.8	0.0003
Milk		{ Buttermilk in vacuum evaporator at 150°F for 42 days	.....	.....	25	0.004	2	0.0003
		{ Condensed sweet milk in vacuum evaporator at 140°F	.....	.....	.....	.....	0.3	0.00005
		{ 14 days	6	0.0001	3	0.0005	1.4	0.0002
		{ Specimens immersed in phenol at 125°F for 6 days	.....	.....	0.4	0.00007	0.3	0.00005
		{ Specimens immersed in phenol at 365°F for 6 days	.....	.....	.....	.....	0.46	0.00008
Pineapple juice		{ Alternate immersion at 75°F for 48 hr	5	0.0008	1.17	0.00003	0.3	0.00005
		{ Alternate immersion at 185°F for 48 hr	39	0.006	23	0.004	2	0.0003
		{ 100 grain vinegar in storage tank for 8 months	2	0.0003	63	0.011	0	0.0000
		{ In preservative for vinegar sugar mixture at 140°F for 85 days	.....	.....	2	0.0003	0	0.0000
		{ In preservative at 155°F for 27 hr	202	0.033	22	0.0035	0.12	0.00002
Vinegar		{ In 190 proof grain spirits for 2 months	0.02	0.00003	182	0.029	0.01	0.000002
		{ In bonded rye for 6 days	5	0.0008	1	0.00017	0.07	0.00001

\* Nickel and Nickel Alloys, International Nickel Co., New York.



## SURFACE PROTECTION AND CLEANING

During handling, small particles of iron, often in the form of dust and mixed with grease, may collect on the clad surface. A clean appearance can be restored by removing any grease with an organic solvent, such as carbon tetrachloride, trichlorethylene or a hot caustic cleaning solution. Then the clad surface should be washed and scrubbed with a solution of commercial hydrochloric (muriatic) acid (18 to 20° Bé) in the proportion of 1 gal of water to  $\frac{1}{2}$  to 1 gal of acid. This should be followed by a rinse with plain water, which, after wiping to dryness, will leave the clad surface satisfactorily clean. If available, hot water should be used for the rinse as it will leave the surface dry on evaporation.

Finishing operations other than the cleaning method just outlined are not recommended generally. For special applications, polishing may be done, but it is not possible to develop the high finishes that can be produced on cold-rolled surfaces, since the clad plate is a hot-rolled product.

## CORROSION DATA

The successful application of clad steels to prevent corrosion or contamination in a wide variety of processing equipment is on record. As corrosion is a complex phenomenon, a study should be made to determine which material should be used for a specific application or requirement. Consideration should be given a large number of factors including temperature, pressure, agitation, galvanic factors and general experience with similar equipment. Table 11-6 will give an indication of the wide range of corrosive media for which successful use of nickel, Monel, and Inconel have been made.

## Stainless Clad Steel

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Iron and steel are excellent structural materials. Unfortunately, however, they are very readily attacked and waste away even under very mild corrosive conditions. To protect them against the ravages of corrosion or to make them more resistant to industrial environments has been a major problem with metallurgists for many centuries. Covering the surface of iron or steel with thin layers of a more corrosion-resistant metal or alloy readily suggests itself as one solution of this problem. It would, therefore, be surprising if it were found that attempts at producing clad materials had not been made at a very early date.

### HISTORY

Evidence of crude cladding by casting and working is apparent in the hot-hammered ewer, fabricated of copper with a thin coating of silver by the smithy of the second Egyptian Dynasty. The golden "Holy Carpet" woven of silver wire encased in thin gold, was made from clad bars, hot hammered and passed through a series of draw plates.<sup>1</sup> The tin plate introduced in the 15th century by Bohemian iron workers in the Erzgebirge mountains appears to be the first clad incorporating a ferrous core.

More recent literature shows that J. Park, Jr. received a patent<sup>2</sup> in 1868 for a "method of combining copper and cast steel by casting the molten steel on or around the copper which is previously heated . . ." Absterdam, in 1869, patented a Bessemer steel base with a cementation steel coating.<sup>3</sup> Several other patents, supplementing the same general method were issued in this period.<sup>4-6</sup> A method for excluding air from the space between the clad and base components during the high tem-

perature treatment was patented by Fleitmann<sup>7</sup> in 1882. Radig<sup>8</sup> pointed out in 1894 that combinations of metals other than iron or copper could be utilized if the coating metal were the softer of the two.

In 1909 C. Davis<sup>9</sup> apparently was the first to propose the use of the electric arc for producing clad metals. His invention covered the production of armor plate by alloying nickel, chromium, and carbon with the molten metal of a base fused to a depth by closely spaced electric arcs. Later a surface covering of flux was suggested by Berg "to prevent oxidation of the steel during the cladding process."<sup>10</sup> Later patents<sup>11-13</sup> by Simpson, Browne, and Heuser also incorporated the electric arc for welding the clad metal to the core.

Following the introduction of chromium stainless steels in 1916, the advantages of the new steel as a cladding material were soon recognized. Gillespie in 1919 was granted a patent<sup>14</sup> on an article of manufacture consisting of a sheet of mild steel coated on one or both sides with chromium steel "of the kind known as stainless steel." Gillespie's suggested method was to apply the stainless steel to the mild steel billet, bar, plate, or sheet by hammering, rolling, or pressing under the action of heat.

## PRESENT METHODS

Some of the methods for making stainless-steel clads, many of which are in use, may be classified as follows:

**1. Casting Method.** Two stainless-steel plates separated by an inert protective film and sealed (welded) around the edges are centered in an ingot mold, and steel is cast around the plates. The ingot is heated to rolling temperature, and the ingot is reduced to twice the thickness of the required gage. After the edges are sheared, two clad plates result. Double clad can be made by placing two sets of plates in a mold. In this case one double-clad plate and two single-clad plates result. Sheets may be produced from the plates by further rolling.

**2. Fusion Melting.** A granulated mixture of ferroalloys, iron, and so on, properly apportioned to give the desired composition of the clad when melted, is placed on the face of a steel slab, usually together with a suitable material to form a protecting slag. The mixture is melted with electric arcs and thus fused on the surface of the steel slab. The composite slab is then rolled by the usual methods into desired products.

**3. Intermeting.** This is a modified electric-furnace procedure. A refractory mold is built around three sides of a steel slab. Controlled electric arcs start melting the steel-slab face at the bottom of the mold,

together with the requisite ferroalloys and other metals necessary to give the desired composition under a protective slag. These ferroalloys together with the other necessary metals are fed continuously in controlled proportion and amount while melting is in progress. As the metal is melted, the arcs travel upward until the mold cavity is completely filled. When double-clad stainless is desired, the operation is repeated on the opposite slab face. The composite slab is then reduced by usual methods into the final size and form.

**4. Sandwich Method.** In this method, the clad face is united with the base metal by pressure, usually rolling, at high heat. Two stainless sheets may be plated on one side with 0.010- to 0.020-in.-thick deposit of electrolytic iron. The unplated sides of the stainless plates are coated with an inert material and then sandwiched between two thicker steel plates, with the plated sides facing the mild steel. The edges of the pack are completely sealed, usually by welding. The pack is heated usually to about 2200°F and rolled to double the desired gage. As an alternative to plating iron on one side of the stainless plates, nickel may be used or a thin sheet of iron or nickel may be inserted in the pack between the stainless steel and the mild steel plate.

#### NORMAL WELDING METHODS \*

Overlapping beads of weld metal are deposited on the surface of a mild steel plate by the electric-arc, oxyacetylene, or atomic-hydrogen method. The deposited weld metal is cleaned and ground and the composite plate hot-rolled to the desired size.

Spot welding is used particularly with heavy-gage clads. The cladding metal is united to the base by a series of spaced welds. This clad is not continuously bonded.

Stainless-steel sheets are also united to a relatively thick mild steel plate by spot welds which overlap to produce a continuous weld or stream. Adjacent streams may or may not overlap so that the bond can be either homogeneous or intermittent.

Many other methods for producing stainless clads have been covered by patent and attempted on a commercial scale. The extent of the activity in this field may be judged by the number of patents issued, a list of which is appended to this chapter. Practically all of the stainless clad manufactured by steel producers has been made by the casting, intermelting, or sandwich methods, while fabricators of equipment have used modifications of other normal welding methods.

\* See Chapter 14 for a further discussion of welding methods.

## AVAILABLE MATERIAL

At present stainless clads are confined to flat products—plates, sheets, and strip by some of the methods now in vogue. Both single- and double-clad stainless steel are available. The usual thickness of the clad face is approximately 20 per cent; that is, the thickness of the stainless face is approximately 20 per cent of the total thickness of the composite for single clad. For double clad the usual thickness for each face is approximately 20 per cent of the total thickness. However, some manufacturers are prepared to furnish single-stainless-clad steels in which the thickness of the stainless clad face is varied in increments of 5 to 50 per cent of the total thickness.

Although there are no definite limitations as to the thickness of clad sheets, in some cases the thickness of stainless-steel sheets has been limited to 18 gage (0.050 in.) for single clad and 22 gage (0.031 in.) for double clad. Clad plates are usually confined to thicknesses of  $\frac{3}{16}$  in. and greater. The limitations as to length and width are approximately the same as for solid stainless grades.

TABLE 12-1. COMPOSITION OF STAINLESS-STEEL TYPES (AISI)

Type	Carbon	Manganese	Silicon	Chromium	Nickel	Other
302	0.08-0.15%	2.00% max.	1.00% max.	17.00-19.00%	8.00-10.00%	
304	0.08% max.	2.00% max.	1.00% max.	18.00-20.00%	8.00-11.00%	
316	0.10% max.	2.00% max.	1.00% max.	16.00-18.00%	10.00-14.00%	Molybdenum 1.75-2.75%
347	0.10% max.	2.00% max.	1.00% max.	17.00-19.00%	9.00-12.00%	Columbium 10 X carbon min.
410	0.15% max.	1.00% max.	1.00% max.	11.50-13.50%	.....	
430	0.12% max.	1.00% max.	1.00% max.	14.00-18.00%	.....	
446	0.35% max.	1.00% max.	1.00% max.	23.00-27.00%	.....	Nitrogen 0.25% max.

Almost all types of low-carbon stainless-steel clads can be made, but some types, such as 302, 304, 316, 347, 410, 430, and 446, are more readily available than others.

Stainless clads are also available in the form of strip, but strip has been largely confined to double clad.

## CORROSION RESISTANCE

The corrosion resistance of the stainless-steel clads is equal to the corrosion resistance of solid material of the same type, provided it is within the same range of chemical composition. When heating operations such as hot forming or welding are involved in fabrication with

clads of the chromium-nickel types, the same precautions as those used for the solid types must be observed if maximum corrosion resistance is to be maintained. Briefly, when the chromium-nickel stainless-clad steels are held in the range of 800° to 1500°F, carbides are precipitated at the grain boundaries on the stainless face. In this condition when corrosive media are present, these stainless faces are susceptible to rapid intergranular attack with the result that disintegration takes place. It is, therefore, necessary that steels with cladding of this composition be fully annealed after heating in this range if they are to be used under corrosive conditions. Where annealing after fabrication is not practicable, then austenitic chromium-nickel steels containing columbium (type 347) or titanium (type 321) should be used for the cladding. Where welding is used, it is possible, by good welding practice, to weld thicknesses up to approximately  $\frac{7}{16}$  in. of the chromium-nickel types which contain 18 per cent minimum chromium and 8 per cent minimum nickel without annealing after the welding operation. Where annealing is impracticable or greater thicknesses are involved, steels containing either columbium or titanium, as previously mentioned, should be used as cladding.

It is also obvious that for high-temperature service in the 800° to 1500°F range, or if service is at higher temperatures and involves slow cooling through this range and where corrosive conditions are involved, stainless clads of the 18 per cent chromium-8 per cent nickel type must contain either columbium or titanium in welded structures; the deposited weld metal should also contain columbium.

#### ANNEALING AND PICKLING

There are certain inherent difficulties in the manufacture of stainless-steel clads which pertain chiefly to the producer of flat products, although the same problem would extend to the fabricator of equipment when annealing and large flat surfaces are involved. Because of the difference in the coefficient of expansion of the clad stainless face and the steel backing, single-clad sheets and plates curl up badly on heating, thus making the material not only difficult to handle but also more difficult to flatten than solid material. Because of the greater difference in the coefficient of expansion more difficulty is experienced with the chromium-nickel than with the straight chromium types. These difficulties are not encountered with double-clad stainless or when annealing small shapes with curved surfaces or large circular vessels with dished heads made from single clad.



The annealing temperatures, because of the steel backing, are usually lower than those used for solid stainless. Both the chromium and chromium-nickel stainless-clad types are usually open annealed. Common annealing temperatures and methods are shown in Table 12-2 for some of the most popular types.

TABLE 12-2

Type	Temperature, °F	Time
446	1550-1600	4 hr at temperature, air-cool to 1300°F and water-quench.
410 and 430	1300-1350	¼ hr minimum or 1 hr per inch of thickness, air-cool.
304	1825-1875	¼ hr minimum or 1 hr per inch of thickness, see text.
316	1900-1950	¼ hr minimum or 1 hr per inch of thickness, see text.
347	1800-1850	¼ hour minimum or 1 hr per inch of thickness, see text.

The austenitic types such as 304 and 316 must be heated rapidly to temperature and cooled rapidly to black, the time to reach black not exceeding 3 min. The cooling rate on type 347 is not important.

TABLE 12-3. PROPERTIES OF SINGLE-CLAD PLATE \*

Clad Type	Tensile Strength, psi	Yield Point, psi	Elong. ‡ % in 2", min.	Elong. % in 8", Min.	% Clad, Approx.
410	55,000-65,000	0.50 T.S.	27.0	25.0 §	20
430	55,000-65,000	0.50 T.S.	27.0	25.0 §	20
446	55,000-65,000	0.50 T.S.	27.0	25.0 §	20
302	55,000-65,000	0.50 T.S.	27.0	25.0 §	20
309	55,000-65,000	0.50 T.S.	27.0	25.0 §	20
316	55,000-65,000	0.50 T.S.	27.0	25.0 §	20
347	55,000-65,000	0.50 T.S.	27.0	25.0 §	20
430 †	65,000-77,000	0.55 T.S.	21.4	22.7	20
446 †	65,000-77,000	0.55 T.S.	21.4	22.7	20
347 †	65,000-77,000	0.55 T.S.	21.4	22.7	20

\* ASTM Specifications A70 or A201.

† C-Mo backing. ASTM Specification A204.

‡ Based on maximum tensile, ASTM formula  $\frac{1,750,000}{\text{tensile strength}}$  for thickness to 2½ in., inclusive.

§ Based on maximum tensile, ASTM formula  $\frac{1,550,000}{\text{tensile strength}}$  for thickness ¼ to ¾ in., inclusive, subject to minimum of 25 per cent.

|| Based on maximum tensile, ASTM formula  $\frac{1,650,000}{\text{tensile strength}}$  for thickness ¾ to 1½ in., inclusive.

Because of the steel backing of single clads, pickling solutions that are ordinarily used with solid stainless must be avoided because of

their rapid attack of the steel base. Stainless clads of the 300 series, with the exception of types 321 and 347, should not be pickled unless the carbides are in solution as they will be rapidly attacked by the pickling solution. For pickling stainless clads, a solution of 8-12 per cent by weight of sulfuric acid and containing a commercial inhibitor may be used. Temperature of pickling solution may vary between 150° and 180°F, depending on the grade and the time held at temperature. The time required will vary between 15 and 40 min.

After pickling in this solution and water washing, a quick immersion in a 10 per cent nitric acid solution by volume at 150°F followed by water washing may be used to whiten the stainless face.

### MECHANICAL PROPERTIES

The mechanical properties of stainless clads will vary with the thickness of the clad surface and the composition of the backing material. Usually a low carbon (0.08-0.10) steel is used. Table 12-3 gives typical values that are to be expected with a 20 per cent single clad, annealed as indicated. When stronger backing steels are used, an increase of strength is obtained.

### FABRICATION

Considerable damage can be done in welding stainless clad if the recommendation that clad be treated as mild steel plate is taken too literally. Appropriate welds exhibit corrosion resistance equivalent to the rest of the cladding. Stainless-clad steel is adaptable to welding by gas or electric methods. Successful procedures have been worked out to produce lap, butt, V, and flange welds. For thin gages (16-10 gage) close-fitting butt welds may be made by using an alloy welding rod, the weld being initiated from the stainless side.

Where fabrication entails deep drawing, clad steels, under some conditions, may show some advantage over solid types. Where the power of the drawing press is limited and solid stainless steels of the 18-8 type are involved, because of their rapid work hardening, it may be necessary to introduce intermediate anneals which may not be found necessary when drawing stainless clads of the same type. A cobalt-type high-speed tool has been found satisfactory for machining any stainless clad, especially those not fully annealed.

Though clad plates are fabricated with the same general technique as monometals, details will vary. Fabricators familiar with the indi-

vidual reactions of their clad products can furnish pertinent information.

### USES

Stainless-clad steel has bridged the gap for such uses where solid stainless would prove too costly and chromium plating impractical. In clad sheets, however, differentials in cost are not so great as with heavier plates. To determine the advantages of stainless clads, each case must be considered separately and the advantages and disadvantages carefully weighed against the use of a similar type of solid stainless. However, stainless clads are widely used, and some of the more important applications are enumerated in the following paragraphs.

The automotive industry was one of the first large-scale consumers of stainless clad when it was introduced in 1931. Reports current at that time enumerate successful utilization of composite metal for the central element of wooden spoke artillery wheels, bumpers, and body hardware. Clad has also been found advantageous for large-size equipment, particularly for service involving high pressures, temperatures up to 800°F, and cyclic temperatures. Consequently, many large units have been made for the processing industries. Food industries have used smaller-size units. In many instances of such application, no particular corrosive media are encountered. However, clad is used to protect the foodstuffs, prevent the discoloration of liquids, or simply for aesthetic value. The brewing industry utilizes stainless-steel clad for fermentation tanks; the paper industry, for the production of wood pulp by the sulfite process. In the latter instance, clad supplants brick and lead linings. Finally, there are the prolific uses of flat-rolled stock as stampings, architectural trim, table tops, and containers. Where heat-transfer properties are important, the thermal conductivity of clad stainless steel may offer some advantage over solid stainless, particularly in the heavier gages. Considerable tonnage of double-armored clad strip and sheet is fabricated into cooking utensils because of thermal superiority.

Stainless-steel clads are used extensively in the petroleum industry, particularly where sour crudes are encountered, where it has conserved several thousands of tons of mild steel.

Clad metal is, of course, limited to those applications where a continuous clad surface is exposed. Though used for some mining equipment, clad would not ordinarily be used for ore graders, or similar equipment which would involve pierced metal.

The history of clad metal has been long and varied. From all indications the future of stainless-clad steel will be equally so, keeping pace with the ingenuity of the design and process engineer.

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## Cast Laminated Metallic Materials

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Cast laminated metallic materials have been made in many varieties to meet engineering needs. A classification of some of the procedures employed follows:

- (a) Chill-cast metal.
- (b) Chill- or sand-cast duplex metal.
- (c) Solidified casting surface coated with liquid metal.
- (d) Casting surface coated by absorption of alloys.
- (e) Weld-coated casting surfaces.
- (f) Spray-coated casting surfaces.
- (g) Dip-coated casting surfaces.
- (h) Electroplated casting surfaces.

### CHILL-CAST METAL

Cast iron is unique among the metals in providing a homogeneous liquid composition which can be cast into a mold to form structures possessing widely different properties. Cast iron is a high-carbon iron alloy containing silicon up to 3.00 per cent as an additional constituent. Silicon supplies the graphitizing power necessary to precipitate carbon as graphite from the very hard iron-carbide component called cementite. When a casting that is low in silicon content is processed to cool slowly while its surface cools at a fast rate, it becomes possible to prevent graphitization in the rapidly cooled surfaces. The speed of cooling in this case freezes the metal so that a considerable amount of hard iron carbide forms at the surface while the internal portions of the casting contain graphite which has had time to precipitate under conditions of relatively slow cooling. The structure at the surface will then possess a hardness of approximately 500 Brinell, while the core of the casting

may be as soft as 180 Brinell. The surfaces of castings of this type are said to be composed of white iron which refers to the absence of graphite in the structure, whereas the core of the casting is composed of gray iron which consists of finely divided graphite embedded in a steel matrix. Thousands of tons of castings of this type are produced annually, mainly for such applications as railroad-freight-car wheels, rolling-mill rolls for the metal industry, and chilled rolls for use in the

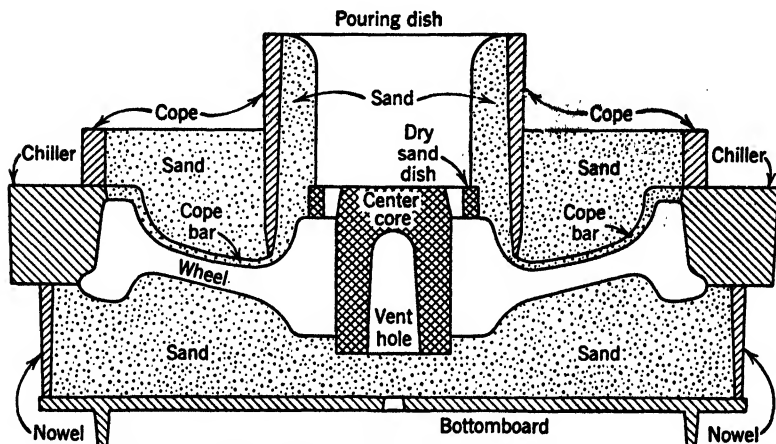


FIG. 13-1. Cross Section of Wheel Mold Used in Car-Wheel Manufacture. Chiller produces white-iron rim, while flange and hub embedded in sand produce gray iron. (Courtesy F. K. Vial, Association of Manufacturers of Chilled Car Wheels.)

paper and rubber industries, as well as for pulverizing and conveying equipment. In addition, many irregularly shaped commercial castings such as plow points, dies, scoops, buckets, and chutes are made of this type of material.

As a typical example of the process, Fig. 13-1 illustrates the mold used in the casting of car wheels, whereas Fig. 13-2 illustrates the structure at the surface of the resulting casting. Figure 13-3 demonstrates varying thicknesses of chilled surface which result from alteration in the composition of the liquid metal.

Most other cast metals such as steel and the nonferrous metals and their alloys develop structures that are comparatively homogeneous when cast under conditions that provide differences in the rate of cooling. In most commercial applications of these alloys, the practice of chilling is employed principally to densen the surface metal. The

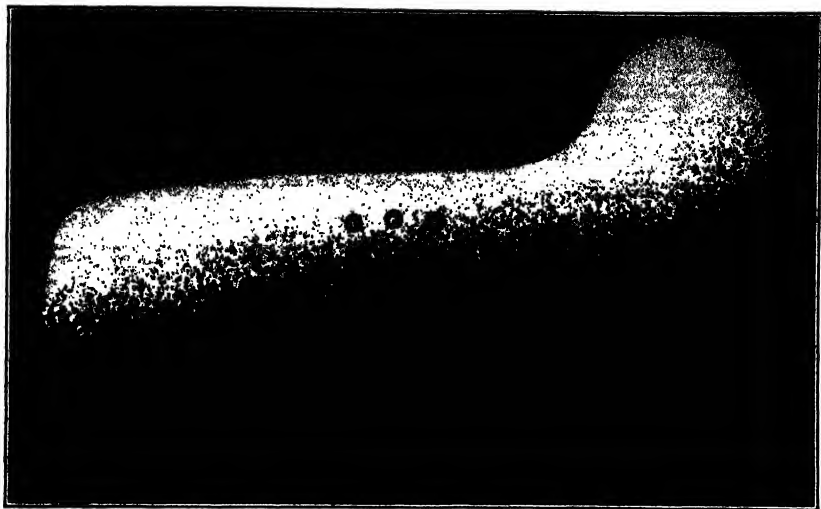


FIG. 13-2. Fracture across Rim of Experimental Wheel Shows White-Iron Tread Backed by Gray Iron (3 spots mark hardness test indentations). (Courtesy F. K. Vial, Association of Manufacturers of Chilled Car Wheels.)

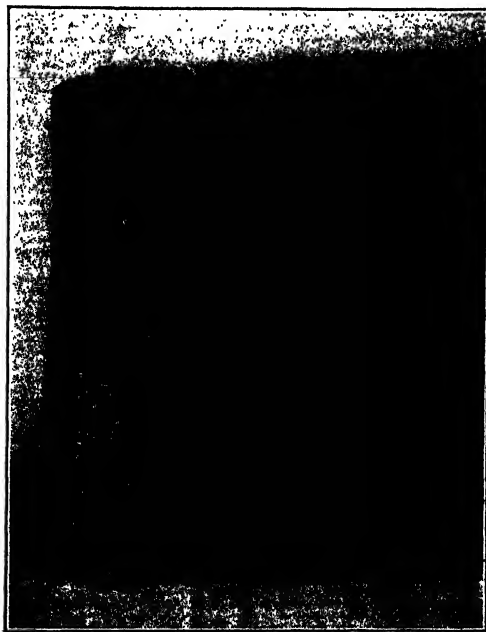


FIG. 13-3. Fractures of Test Bars, Bottom Face Chill-Cast Demonstrating Variation in Thickness of White-Iron Surface. (Courtesy A. P. Gagnebin, International Nickel Company, Inc., Bayonne, N. J.)



densened condition does not alter the structure and mechanical properties so markedly as it does in certain chill-cast iron alloys.

The foregoing description refers to metals of a single composition that have been poured into a casting or mold. The process of pouring two metals into a single mold has been practiced for many years, and some of the variations of this procedure are described in the following text.

#### CHILL- OR SAND-CAST DUPLEX METAL

Foundrymen have for many years practiced the art of making castings of composite metals. In the earlier stages of the art, a soft metal usually followed a hard one in the mold, so that a wear- or abrasion-resisting surface was provided on the casting, whereas the core consisted of softer metal which could be readily machined. The practice can be reversed and a soft metal cast first to be followed by a hard one. Some of the earliest examples of this art occurred in the form of small rolls in which the hard shell was cast, followed by a rapid removal of the core, while the cavity remaining was filled with new liquid metal which when solidified was softer in character.

Another type of casting which lent itself to a somewhat simpler procedure was the lathe bed or machine-tool frame whose wearing surfaces were located in the bottom of the mold, while the aprons and stands extended upward in the mold. In molds of this type, two pouring basins could be led to the casting, with the basin that led to the bottom bringing in a harder wear-resisting metal, while the second basin accommodated the flow of soft metal which was fed into the mold at an upper level as soon as the required quantity of hard metal had been poured. This pouring in tandem produced a casting, one portion of which was specially composed of a harder material better to resist wear in the service to which the casting was subsequently subjected, while the remainder of the casting was composed of a soft grade of iron.

Later developments in this art led to the production of special shapes such as rolling-mill rolls. At the present time some of these castings are made with a very hard crust or shell of chilled alloyed cast iron, while the core and necks are filled out with a soft machinable iron. Daniels <sup>1</sup> describes the manufacture, properties, and structure of certain composite rolls and mentions their cost as greater than that of chilled-cast iron but much less than that of forged and hardened steel rolls. Figure 13-4 shows one of these rolls ready for delivery.

Atkin <sup>2</sup> describes three general methods of practice that have been developed to evolve this product. In one of them the entire mold cavity

is filled with metal of the hard chilled-iron composition which is allowed to stand long enough for the surface crust to form. The filled mold is then flushed out with the soft cast-metal composition and enough of the core metal removed by this means to provide soft machinable necks. In a second method the soft metal is poured into the mold through a feeder head and the hard metal forced back up the downgate until the necessary amount of hard metal has been displaced. In the third method which is a modification of the first, an outlet gutter for the hard metal is provided at the top of the roll. Since this casting is

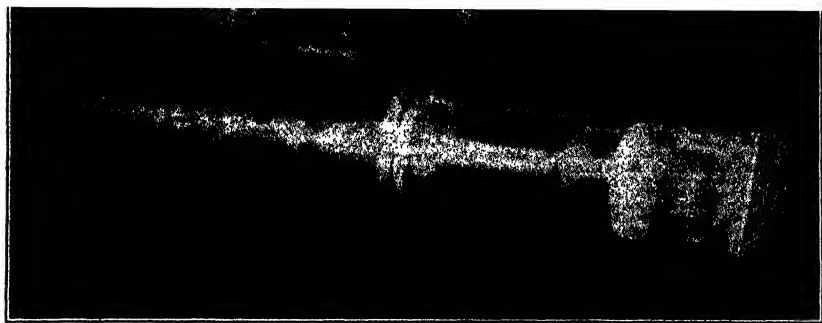


FIG. 13-4. Typical Composite Roll. Barrel surface metal contains extremely hard and wear-resisting chilled iron (Ni-Hard), while core and necks consist of softer machinable metal. (Courtesy F. C. T. Daniels, Mackintosh-Hemphill Company.)

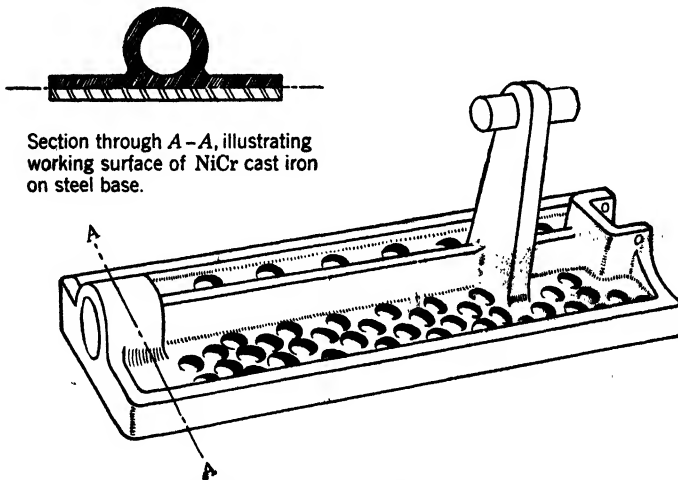
poured against a chill in the barrel section of the roll, while the necks are not in contact with the chills, the operation becomes practical because the chill helps form the surface crust.

In another example of this type of procedure, the mold cavity is filled in the same manner and then allowed to stand for a short but specific time interval, during which the hard metal crust forms against the chill. The mold is then drained, leaving the hard surface crust. The drain is then plugged and the mold cavity refilled with soft metal, thus providing machinable shoulders and necks along with a hard surface on the barrel or body.

It is obvious that the composition of the core metal in these practices can be varied through relatively wide limits to provide the quality desired for the final product.

Dissimilar metals such as cast steel and cast iron have been poured to form a composite casting of the grate-bar type shown in Fig. 13-5. The grate mold is poured with molten steel in the lower part to provide a crank and rib section of high strength and toughness. After a short

time interval, the cast-iron portion of the mold is filled and overflowed into the risers, providing for a perfect fusion at the steel-cast-iron



Section through A-A, illustrating working surface of NiCr cast iron on steel base.

Fig. 13-5. Grate Bar Consisting of Cast-Steel Base and Cast-Iron Working Surface.

interface. Such castings combine the toughness of steel with the resistance to warpage and deterioration that cast iron possesses for the service to which they are exposed.



Fig. 13-6. Fracture of Centrifugally Cast Tube Showing Hard White-Iron (Ni-Hard) Surface Bonded to Gray-Iron Core. Actual size. (Courtesy Dr. A. E. Schuh, United States Pipe & Foundry Company, Burlington, N. J.)

Two different aluminum alloys have been used to make pistons in which the head of the piston consists of Y Alloy which is resistant to

heat, while the skirt of the piston is made from a silicon-aluminum alloy. In practice two ladles are used. The mold is arranged with the piston head down. Y Alloy is poured in, followed immediately by the second alloy which fills the mold. A good bond and diffusion is assisted by the lower density of the silicon-alloyed aluminum.<sup>3</sup>

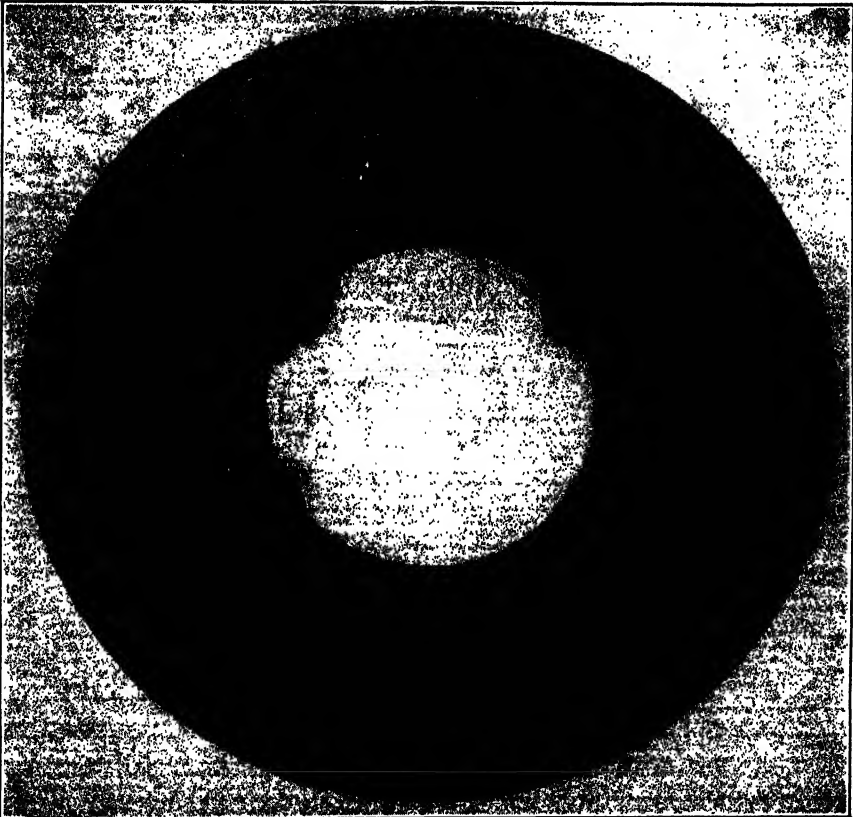


Fig. 13-7. Macroetched Section of Tube Showing Ring of Hard Outer Metal Bonded to Core Metal. Actual size. (Courtesy Dr. A. E. Schuh, United States Pipe & Foundry Company, Burlington, N. J.)

Another recent development involves centrifugally cast tubular products which can be produced with a surface metal of one composition and a core metal of another. The practice consists of timing the flow of the two separate metals into the revolving centrifugal mold so that each freezes at its proper time to take its place in the composite casting. The procedure has been experimentally applied to composite

cylinders with a hard (Ni-Hard) surface accompanied by a core of readily machinable gray iron. Other metals such as Ni-Resist for corrosion resistance can be similarly bonded with plain gray iron to form a composite product. Since these products are made by the centrifugal process, it is possible to adjust the thickness of the metal in the shell by volumetrically measuring the amount necessary. The illustration shown in Fig. 13-6 consists of a Ni-Hard shell about  $\frac{1}{2}$  in. thick which was made to provide a  $6\frac{1}{4}$ -in.-outside-diameter tube with a  $4\frac{1}{4}$ -in.-inside-diameter center, of which the internal portion consisted of gray iron. By this means it is possible to obtain an excellent bond, and Fig. 13-7 shows that a sharp fusion zone has been obtained of uniform circumference.

#### SOLIDIFIED CASTING SURFACE COATED WITH LIQUID METAL

By far the most common method of producing composite metal castings consists of covering a solid metal or casting surface with a second material usually applied in the molten state to effect a fusion at the interface. For example, stainless steel can be bonded to gray iron or carbon steel, whereas in other cases dual-metal castings can be produced in which the different metals are applied with the object of having each serve its purpose most economically in the composite-metal article. An early example of this procedure occurred in the course of the production of air-cooled automotive cylinders a generation ago. At that time, metallic-copper fins were set into a mold and fused to the cast-iron cylinder block to provide a high thermal conductivity for the radiation of heat from the cylinder, while at the same time a good metal wearing surface was obtained on the inside diameter of the cylinder. More recently the popular use of aluminum to provide light weight and high thermal conductivity has led to the development experimentally of air-cooled motor cylinders in which a cast-iron or Ni-Resist sleeve suitably fluxed is inserted in the mold which is then filled with aluminum alloy to complete the cylinder castings. This construction combines the good wearing quality of the cast-iron alloys for the inside of the cylinder, whereas the jacketing material combines light weight, rigidity, and thermal conductivity to complete the functioning of the assembly. Thermal expansivity becomes a factor, and the desirability of bonding a high-expansion cast iron such as Ni-Resist with an expansivity of 0.000010 in. per degree Fahrenheit with a low-expansion aluminum with an expansivity of 0.000105 in. per degree Fahrenheit becomes an important factor in the problem. Jardine's<sup>4</sup> work describes mechanical assemblies of this type.

Similar assemblies made by bonding aluminum to steel or cast iron either by casting or brazing the aluminum casting around the sleeve insert have been described in various publications. The patent literature recently contains many citations. For example, Van Amerongen



FIG. 13-8. Diesel-Engine Piston of Cast Aluminum with Cast-in Crown and Top-Ring Grooves of Ni-Resist to Provide Heat and Wear Resistance with Expansivity Approximately Equal to That of Aluminum.

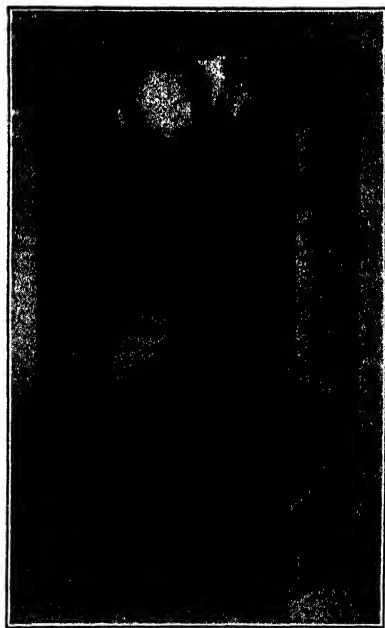


FIG. 13-9. "Y" Alloy Piston for a High-Speed Diesel Engine with Cast-in Ni-Resist Inserts for the Upper Piston Rings. This method of manufacture provides a hard wear-resistant surface as a facing for the grooves. (Courtesy Specialloid, Ltd.)

and Boyce,<sup>5</sup> Deputy<sup>6</sup> and Irgens<sup>7</sup> describe casting a metal around a sleeve insert in a mold to obtain a composite metal article. Whitfield and Sheshunoff<sup>8</sup> describe aluminum castings bonded to steel sleeves to make aircraft-engine cylinders.

The same general features of composite construction have been employed in making aluminum pistons. Bryan<sup>9</sup> describes cast-aluminum

Diesel-engine pistons made with a crown of heat-resisting alloy, mechanically attached. Aluminum pistons have also been made with piston-ring carriers or grooves made of heat- and wear-resisting metals such as Ni-Resist, whereas in other cases aluminum piston heads have been protected from erosion at high temperatures by casting into them inserts of heat-resisting alloys (see Figures 13-8 and 13-9).



FIG. 13-10. Cross Section of Typical Centrifuse Brake Drum Showing Steel-Backed High-Carbon Nickel-Chromium-Molybdenum Alloyed Cast-Iron Braking Surface. (Courtesy Motor Wheel Corporation, Lansing, Mich.) The composition of Centrifuse drum iron conforms to the following range:

Total carbon	3.70/3.90%
Silicon	1.45/1.65%
Nickel	1.35/1.55%
Chromium	0.30/0.40%
Molybdenum	0.30/0.40%

Bimetallic castings have also been employed for glass molds and glass-mold plungers.<sup>10</sup> These castings are made by heating the insert, which is ultimately the working surface, to a red heat and then placing this heated unit into the mold, after which liquid cast iron is poured around it. Alternately, a cast-iron mold is prepared and the surface to be coated is machined, after which it is brought up to a red heat, and a special alloy is poured into the cast-iron mold, effecting a bond and ultimately providing a special alloyed working surface. The special alloys in these applications are usually members of the family of corrosion- and heat-resisting stainless-steel or cast-iron alloys of the Ni-Resist type, whereas in other cases low-expansion alloys of the 35 per cent nickel type may be used.

Composite-metal castings are frequently made by the centrifugal process by fusing one of the metals to a solid shell. In the production of automotive and aircraft brake drums,<sup>11</sup> it is customary to preheat the shell of the drum, apply a suitable flux, and then pour the required amount of liquid cast iron into the mold. A junction is effected between the two metals, and the high wear-resisting quality of the cast iron is combined with the strength and resistance to breakage of the steel. Figure 13-10 illustrates a cross section of this type of product.

Tubular products of bimetallic castings made by pouring a liquid metal against a solid tube have also become common commercial products. Knipp<sup>12</sup> describes composite castings of cast steel and red brass for railway bearings, effecting a saving of 75 per cent of the brass. Stuffing box glands, spindles, plug cocks, and the like have been successfully made. Usually the outer shell, which may be a wrought metal or cast metal, is prepared and fitted into a centrifugal casting mold which rotates, while the second metal of the system is poured and centrifuged into a bond with the inner surface of the shell previously prepared. Some reference to these practices appears<sup>13</sup> which mentions the production of combination of steel, cast iron, or nonferrous materials by this process. Another reference<sup>14</sup> describes details of peripheral speed during pouring, time in the mold, conditions of cooling, and the like for combinations of ferrous and nonferrous alloys such as steel-bronze or cast iron-bronze or aluminum-bearing metals.

The coating of the cylinders for mud pumps used for the drilling of oil wells has become a commercial process in which a steel sleeve is heated and then rotated in a centrifugal device. A low-melting-point cast-iron-base alloy containing nickel and boron in suitable amounts is introduced in the cylinder and allowed to spread evenly over the rotating surface. The composite-metal pump cylinder then possesses high strength resulting from its steel or strong backing metal, while the working surface is composed of a hard abrasion-resisting alloy. The

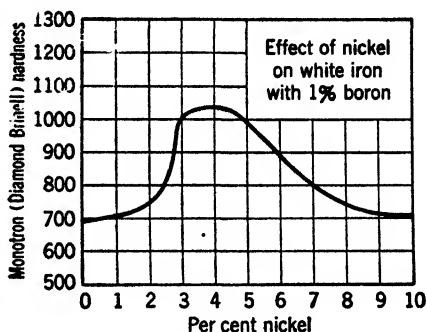


FIG. 13-11. Nickel Additions to a Boron-Alloyed White Cast Iron Achieve Maximum Hardness at 3 to 6 per cent, Providing Basis for Hard-Surfacing Alloy. (Hirsch, Ref. 15.)



low-melting-point material in this case is a ferrous alloy of the following percentage composition: <sup>15</sup>

Carbon	Boron	Silicon	Manganese	Nickel	Phosphorus	Sulfur
2.50-3.25	0.70-1.10	0.50-1.50	0.50-1.25	3.50-4.50	0.05 max.	0.05 max.

Figure 13-11 illustrates the hardness of the abrasion-resisting alloy, while Fig. 13-12 illustrates its microstructure.



FIG. 13-12. Microstructure at Junction of Steel (top) with Hard Nickel-Boron Alloyed Cast Iron (bottom). Magnified 200 $\times$ . (Hirsch, Ref. 15.)

The same alloy has been applied to the exterior of cylindrical objects by fitting a heated cylinder in the centrifugal machine and allowing the fusible special alloy to fill the space between the heated sleeve and an outer jacket so that a cylinder with an external layer of hard surface metal results.

## Casting Surface Coated by Absorption of Alloys 475

Among the nonferrous alloys, many examples exist in which a base metal of steel, cast iron, copper, and so on is provided with a bearing-metal surface such as babbitt or bronze by cleaning, tinning, or providing a chemically clean surface to which bearing metal is bonded. In some of these operations it is customary to facilitate bonding at the interface by coating the base metal with copper or some similar metal which is readily fusible in the dissimilar metals which ultimately form the composite-metal bearing. Many of the bearings for the automotive and railroad industries are made by these methods. A recent reference to automotive bearings of a copper-lead base, alloyed with nickel, tin, or silver, and fused to a steel backing, was described by Lamb and Jeter.<sup>16</sup> Composite bearings of babbitt-lined bronze backed up by steel or malleable iron for use in railroad service were recently described by Pearce.<sup>17</sup>

Wear-resisting coatings of high hardness have been produced by casting on an overlay of low-melting-point material which solidifies to produce a hard surface when cold. The practice has been described by Smith.<sup>18</sup> The part to be coated is preheated, and the cast-on material possesses sufficient solvent power to bond with the base metal and also sufficient elasticity while hot to adjust it to the shape desired.

Wear-resisting inserts of alloys such as manganese steel or Ni-Hard have been made integral with a cast-steel or cast-iron supplementary member to form such parts as hammer-mill bars or rolls for pulverizers.

A hollow hardened cast-steel gear blank has been set up in a core of a camshaft mold and cast iron poured through the blank to form the completed camshaft in a process recently described for the British-built Ford motor.<sup>37</sup> The gear blank is machined, and finally gear teeth, as well as cams, are flame-hardened.

### CASTING SURFACE COATED BY ABSORPTION OF ALLOYS

A limited field of metal-clad castings has been developed in which the casting surface is locally impregnated with a second metal or alloy by absorbing the alloying element from the surface of the mold. Some examples of this practice were exploited about 1915 in the Stroh<sup>19</sup> process in which an effort was made to produce an austenitic manganese steel skin on a casting of steel. The procedure consisted of impregnating the mold surface with a concentrated manganese alloy and depending on the liquid metal to absorb and diffuse the alloy on contact with the mold, thus developing the composite-metal casting. The

cladding in these cases was comparatively thin. At about the same time, references<sup>20</sup> appeared describing the use of 98 per cent manganese flour, mixed with linseed oil and applied to a mold as a wash for a thickness of  $\frac{1}{16}$  to  $\frac{1}{8}$  in. The mold was then baked, steel poured in, and manganese absorbed to form a "wear-resisting skin." Cast-steel electric-railway-car 30-in. wheels<sup>21</sup> with rims and flanges of manganese steel were also described and reported to run 100,000 to 200,000 miles under a 30,000-lb car at 45 miles per hour. These early examples of manganese-impregnated castings may occasionally be duplicated to-day, but their failure to survive and prosper suggests that the practice is economically unsound.

The same procedure has been extended to form a hard white-iron surface on soft gray-iron castings through the practice of alloying the casting surface with tellurium.<sup>22</sup> Efforts have also been made similarly to impregnate ferrous-metal casting surfaces with chromium to arrive at some approach to the stainless-steel compositions.

A British development<sup>23</sup> mentions making a mold with a destructible lining of felt or open-mesh fabric which is impregnated with the selected powdered metal. When metal is poured into the mold, the fabric is destroyed and the residue left free to be absorbed in the casting surface. In most cases of this kind, the need to develop a high order of skill to obtain a fusion with the coating and similarly to prevent a transport of the coating from the surface of the mold to some undesirable location impedes the progress of this practice.<sup>24</sup>

The cementation of metals and alloys in the solid state to solid casting surfaces has also led to the development of dual-metal shapes in which one or more of the parts consist of castings. Heat-resisting surfaces have been produced by alloying surface layers with aluminum as in the "calorizing" process.<sup>25</sup> In this process, aluminum at a temperature of 1500–1800°F diffuses for 6 to 48 hr into the casting surface until the desired depth of coating has been achieved.

A process of impregnating iron and steel castings with silicon to acquire an alloyed surface possessing a composition approximating that of 14 per cent silicon iron, has been described by Ihrig.<sup>26</sup> In this process, articles that are to be treated are heated in a furnace to 1800°F in contact with silicon carbide and chlorine. A concentration of 14 per cent silicon in the alloyed surface and a penetration of 0.015 in. per hour is expected. Valves, fittings, pump parts, and similar castings are expected to acquire an increased resistance to corrosion when treated in this manner.

## WELD-COATED CASTING SURFACES

Castings are frequently coated over their entirety or over local surfaces that are susceptible to damage, to provide them with the protection which special alloys or similar high-grade materials afford. Such clad surfaces can be protected against abrasion, heat, or corrosion by applying an overlay of special material by means of the welding process. In some special cases it may be desirable to attempt to obtain protection against all three of the common destructive agents, namely, abrasion, heat, and corrosion, by applying an alloy coating that possesses a high order of resistance to all these destructive factors. Because another section of this book \* deals in detail with hard surfacing by fusion welding, brief mention is made here only of weld-coated surfaces, to provide resistance to (1) heat and (2) corrosion.

## Heat-Resisting Overlays

Heat-resisting overlays are applied by welding a heat-resisting alloy to the casting, usually in the same manner as indicated for abrasion-resisting materials.\*

Typical applications occur in the cases of steam valves, glass working equipment, hot-forming dies, hot-oil pumps, and the like. Some of these applications involve abrasion resistance as well as heat resistance and an overlay that combines hot hardness with heat resistance may be preferred. Valve parts, such as the seats and disks for high-temperature steam service are frequently overlaid with an alloy coating that combines heat and abrasion resistance.

For years the Mack Manufacturing Corporation has fitted their automotive engines with valve seat inserts<sup>27</sup> composed of a low-expansion "Minovar"-type cast iron coated on its working surface with Stellite. This part combined stability with abrasion resistance at high temperatures at the working surface. The low expansivity of the base-

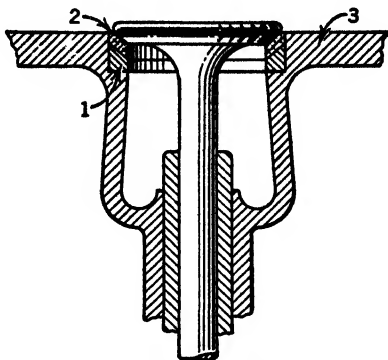


FIG. 13-13. Cross Section of Auto-Engine Valve Seat Showing Composite Insert of Low-Expansion (Invar type) Cast Iron (Item 1) Coated with Hard Heat-Resistant Layer of Stellite (Item 2) in Gray-Iron Cylinder Block Casting (Item 3). (Courtesy Wirrer and Day, International Motors Corporation)

\* See Chapter 14.

metal material provided a secure fit and permanence as an insert in the engine block. Figure 13-13 illustrates the part.

The practice of surfacing cast-steel melting pots or retorts used at elevated temperatures, with a coating of heat-resisting alloy of the stainless steel or high-nickel-chromium type, has been frequently used and at times employed in semiproduction methods for producing a vessel that combines a low initial cost of the base-metal casting with a high resistance to heat provided by the welded-on overlay.

### Corrosion-Resisting Overlays

Corrosion-resisting metals such as stainless steels, Monel, nickel, Inconel, and the copper-base alloys may be applied to large and heavy



FIG. 13-14. Valve Plug Coated with Corrosion-Resistant Overlay.

1. In corroded condition.
2. Machined undersize for overlay.
3. Coated by welding with Monel metal.
4. Finish-machined and ground for return to service.

castings where the critical surfaces can be protected against corrosion. The economy depends on the relation between cost of protected surface and the over-all bulk of the part that is coated. Figure 13-14 illustrates the procedure applied for coating the plug members of cast-steel valves with Monel metal to produce a product of this kind. Steel or cast-iron castings may be treated in this manner to take advantage of the low cost of the base-metal casting. The practice has been applied principally to valve parts where the equipment is used under corrosive conditions in the chemical industry or one of its associated

industries such as the petroleum, paper, or coke manufacturing industries.

Another interesting example of this procedure occurs in the coating of local surfaces of hydraulic turbines in which the runners and possibly the shells consist of very large and heavy castings. Corrosion or cavitation may occur in the early operation of this type of equipment. Since in many cases the exact location of the attack is unpredictable, it has become the custom to allow the attack to develop, after which the affected surface is coated with an overlay of corrosion-resisting material such as stainless steel. Since this operation may need to be performed on a very large casting that cannot be preheated, it is customary to employ cast steel which is better able to resist the tendency toward cracking that may accompany the highly localized heating attending the application of the overlay.

## MISCELLANEOUS COATINGS FOR CASTING SURFACES

As in the case of wrought metals, castings are frequently coated to obtain a composite-metal result for protective or appearance purposes. Coatings are most commonly applied by the (1) spray, (2) dip, and (3) electroplating methods.

### Spray-Coated Surfaces \*

Base-metal castings are occasionally protected from the ravages of corrosion and heat by the application of sprayed coatings. The coatings may consist of any of the more noble metallic elements or alloys. For example, nickel, Monel metal, stainless steel, zinc, cadmium, and lead represent typical coating materials. Cast-carbon-steel pots of the following composition, sprayed with a metallic coating of heat-resisting chromium-nickel alloy followed by a second layer of aluminum, have been described by Keller: <sup>28</sup>

C	Mn	Si	P	S	Cu	Ni
0.35	0.70	0.60	0.06	0.06	Less than 1%	Less than 1%

A casting weighing approximately 1 ton was cleaned and coated with about 0.015 in. of chromium-nickel alloy and then finish-coated with aluminum. In the course of operation at elevated temperatures, some diffusion and alloying followed. The spray-coated pot was reported to deliver approximately 2,000 hr service against 450 for the untreated casting.

\* See also Chapter 15.

Similar practices have been applied to castings exposed to heat or corrosion in the petroleum, chemical, paper, and allied chemical processing industries.

The Sherardizing process of zinc coating is widely applied to cast parts such as malleable or gray-iron plumbing goods and pipe fittings. Chromizing or the process of impregnating solid surfaces with chromium has not been widely developed insofar as castings are concerned. Both processes are well described in existing handbooks.<sup>29</sup>

### **Dip-Coated Surfaces**

The dip coating of castings has been widely practiced, particularly in the manufacture of pipe fittings and plumbing goods. Lead and zinc coatings which represent the largest tonnage of galvanized goods of the metal industry are most commonly employed. Gray iron, malleable iron, and steel castings represent the foundry products most commonly treated by this process.

Castings for the food-processing industries are frequently tin-coated to provide the necessary appearance, resistance to corrosion, and avoidance of risk from toxic effects. Cooking utensils, meat choppers, and dairy equipment represent typical products. As in the case of galvanizing or similar hot-dip-coating processes, the castings must be cleaned, then preheated, fluxed, and dipped one or more times to acquire satisfactory coatings. A comprehensive description of the tinning of cast iron has been given by Cresswell.<sup>30</sup>

Numerous small castings are dip-coated to provide protective metal surfaces in mechanized processes involving the conveyance of the individual pieces or basket batches through the separate steps of the process to the finished stage.

### **Cold-Dipped Coatings—Plating without Electric Current**

Castings subjected to wear are in some cases coated with a thin protective surface of a metal like tin to assist them in working into their service and avoid the risk of early scuffing, scoring, or galling. Engine parts such as pistons and piston rings may be treated in this manner. The coating may be as thin as 0.002 in. or less. The tinning of aluminum pistons treated in this manner has been described by Finnis.<sup>31</sup>

### **Electroplated Casting Surfaces**

As with wrought metal, castings are electroplated to protect them from corrosion or wear or to improve their appearance. The tinning of pistons and piston rings previously described in the cold-dipped

process has its counterpart in electroplated castings which are surfaced with tin, chromium, cadmium, and similar protective metals. The tinning of piston rings has been described by Smith.<sup>32</sup>

The chromium plating of engine cylinder liners to improve their resistance to wear has been described by Van der Horst<sup>33</sup> and Pyles.<sup>34</sup> Piston rings chromium-plated for service in aircraft-engine cylinders have been described by Jarrett.<sup>35</sup> Many examples of chromium-plated castings treated in this manner to extend their performance under severe conditions of corrosion or abrasion are described in trade periodicals.

The practice of coating castings to improve resistance to corrosion as well as appearance is well known, and such common applications as pots, skillets, and stove parts are everyday examples. Another common application of plated castings is automobile hardware usually composed of zinc-base die castings that are nickel- or chromium-plated. The American Society for Testing Materials has drawn up specifications for minimum thickness of coatings on plated zinc-base die castings, and frequent references to commercial practices appear in various trade journals. Some zinc-base die-cast alloys find their way into household kitchen hardware for which service they are frequently coated with protective coverings of nickel or chromium.<sup>36</sup> Similarly, plumbing goods, such as faucets and drains, and hardware, such as door knobs and window ledges, are commonly plated with white-metal finishes of chromium or nickel plate to enhance their appearance, facilitate cleaning, and resist corrosion.

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## Hardness and Wear Resistance—Hard Surfacing by Fusion Welding \*

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### INTRODUCTION. HARDNESS AND WEAR RESISTANCE

The provision of a hard wear-resistant surface layer on metal parts by fusion welding is one of the most versatile expedients at the command of the engineer. The hard-facing alloys are available in the form of convenient welding rods, and the sources of necessary heat, usually the oxyacetylene flame or the electric arc, are portable, relatively inexpensive, and familiar to engineers and mechanics.

It is the purpose of this chapter to provide information that will be helpful in the selection and application of hard-surfacing welding rods. Welding techniques are described in several current publications<sup>1, 2</sup> and, consequently, will receive only brief mention. Present welding-rod alloys, however, are covered too briefly elsewhere. Partially to remedy this and to present some salient aspects of the metallurgy of hard-surfacing alloys as they affect engineering properties, the *materials* for hard surfacing are featured in this discussion.

The selection of hard facing as an engineering technique is strongly influenced by the need for armoring a part against severe service. In addition, the factor of protection in depth is generally required, though in some field repair work this may be less important than the ease of application.

If superficial protection alone is required, a manufacturer will probably select a case-hardening process, such as carburizing or nitriding,<sup>3-5</sup>

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providing a hard zone a few hundredths of an inch thick to minimize wear; hard chromium plating<sup>6</sup> to discourage scratching; various electroplates or hot-dip coatings to combat corrosion; or perhaps metal spraying<sup>\*</sup> to prevent surface deterioration or to provide heat resistance<sup>7</sup> (aluminum or chromium). All these processes are limited to the thickness of the protective layer that may be obtained practically or economically. If an armor  $\frac{1}{32}$  to  $\frac{3}{8}$  in. in thickness is required, hard surfacing is the preferred choice.

A surface overlay deposited from welding rods may be required for wear resistance, corrosion resistance, heat resistance, or perhaps all three. Other special properties, such as reflectivity, are occasionally necessary. Most hard surfacing is done to prevent wear, however, and subsequent discussion emphasizes this factor.

Wear is a complex subject that must be oversimplified for present purposes. This requires omission of the field of lubricants and their effect on wear, a minimum discussion of metal-to-metal wear,<sup>5</sup> and cautious generalizations in the field of abrasion. Wear has received insufficient attention in engineering literature, and the data available are frequently unsatisfactory. This probably results from the complexity of the problems involved and the lack of a universally applicable wear test, which is currently considered to be an impossibility.

Most comparisons of wear resistance are based on observation of actual service. This has an important practical advantage, because all pertinent variables are necessarily included, but there are serious disadvantages. Although variables are included, they are not always described and are seldom evaluated even semiquantitatively. Translation of data from one service test in terms of another may be difficult therefore. Another objection is the usual lack of precise observation and measurement of wear. Thus, field tests usually yield only qualitative and rather variable results. Nevertheless, they may be quite valuable.

Controlled laboratory tests for wear are very desirable, as they permit establishment of the reliability of the test, ranking of various materials, a study of pertinent variables, and a convenient recheck of questionable results. Many tests have been proposed, but, because of the difficulties that attend their development, few have been standardized and applied to many materials. One that has been studied for about 18 years has been used to obtain the abrasion factors reported herein. It was developed to obtain severe abrasion from very hard

\* See Chapter 15 for discussion of metal spraying.

mineral particles (quartz) under moderate pressure and no impact. It has known reliability and has been validated against well-conducted field tests (ball-mill service). The results can be used for guidance in selecting materials when service conditions are sufficiently similar. In common with all other wear tests, the limitations have not been clearly established; it must suffice to note that it will not rank materials in the same order as a pneumatic abrasion test (sand-blast), nor will it reveal the true merit of very tough materials in service involving heavy impact. It is not representative of metal-to-metal wear.

Interpretation of these laboratory test data should include allowance for the hardness of the abrasive and the relative severity of the conditions. Field circumstances may be quite similar, as is the case for ball-mill liners, or they may be much milder, exemplified by plowshares operating in soft dirt containing very little sand. As the severity of abrasion or the hardness of the abrasive decreases, the relative life of materials with good laboratory abrasion resistance tends to increase.

Hard facing is reputed to increase the life of parts 2 to 25 times. Specific examples include 10 to 18 times the life of plain steel for hard-faced cement mill-grinder rings (with further economy from elimination of 9 replacement shutdowns and 15 to 20 per cent increase in production because of better machine efficiency); 7 to 10 times increase in life of hammer mill hammers; 3 to 15 times greater plowshare life; a tenfold increase for brick machine feeder shoe life after replacement of cast iron; fivefold improvement of vertical pug mill push shoes; in coke manufacture carbon scrapers were increased from a life of 3 days to 75 days by hard facing; coke pusher shoes had wear reduced to about  $\frac{1}{80}$  that of steel; water-cooled pokers were improved from 3 months to 2 years to life; hard-faced power-shovel dipper teeth outwore an ordinary set 7 to 1; tungsten carbide insets increased the life of similar teeth before dulling from 6 to 120 hr, with improved efficiency; and armored dredge cutters outwore steel by 7 to 1.<sup>1</sup>

Steel mills have benefited by hard-facing rolling-mill guides, with a typical increase of ten times in life. This application requires combined heat and abrasion resistance. In one case, a steel plant (in the Pittsburgh district) increased the life of the guides for a 15-in. rolling mill from an average of 600 billets for chilled iron to an average of 150,000 billets per set of guides hard-surfaced with a martensitic cast iron. Scratching of the billets was also eliminated. One steel company is said to have saved \$10,000 per year on one item: hot ingot

grappling tong points. Wood-pulp shredder knives used in the paper industry were increased sixfold in life, with the annual cost per machine reduced from \$2400 to \$180 by associated benefits. Other machinery parts provide a multitude of opportunities for similar savings: tool-steel centers have been increased six times in life; hard-faced cams, 10 times. Engine valves are such an excellent application for hard facing that the procedure has become standard practice for many manufacturers. A PT-boat rocker arm, which had been giving trouble from wear, outlasted the engine after being hard-faced with a martensitic iron, it appearing in perfect shape when the engine was torn down after wearing out (Fig. 14-1).

The diversity of service represented by these examples will explain why many matching laboratory tests have not been devised and also why it is not practical to predict field performance from one wear test. Nevertheless, the test data reported here are valuable for ranking materials and may be used for this purpose if the associated conditions are properly considered.

Other factors besides metal loss contribute to the economies of hard facing. The savings in man-hours, as shutdowns for replacement are avoided, may be considerable. Also, where sharp tools or dimensional stability are important, the judicious application of hard facing may add greater operating efficiency to the benefits of longer life. As an example, where differential wear of base and surface layer occur, the careful placement of deposit will produce a self-sharpening composite. This feature is exploited in dipper teeth, plowshares, and kindred parts.

Certain techniques involving composite tools permit startling economies. Forging dies or cutting tools such as milling cutters and single-point turning tools, when necessarily quite heavy, may within their normal useful life lose only a tiny fraction of their total mass. For the sake of the specialized properties required, they are customarily made of expensive die or high-speed tool steels. In many cases it has been found practicable to make them of 0.30 to 0.40 per cent carbon steel with a working point or surface of a weld deposit similar to the steel required. A 600-lb die may be made thus with perhaps 100 lb of welding rod. It is cast almost to final shape, surfaced, annealed, machined, and hardened at perhaps a 70 per cent saving in labor (because of substitution for expensive die sinking). Furthermore, because of superior properties of the weld metal a life increase in a 7:2 ratio resulted in one example.

The savings from tool bits results differently; an insignificant quantity of high-speed steel deposit serves for short runs with special tools,

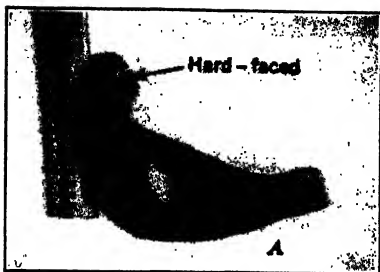
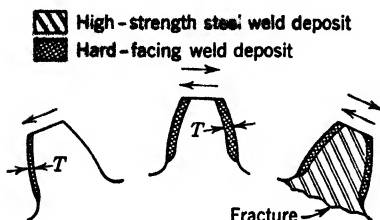


FIG. 14-1A. PT Boat Rocker Arm, Hard-Faced at the Critical Wearing Point with a Martensitic Cast Iron. The procedure changed the part from a problem to an item that outwore the motor.



$T = \frac{1}{16}$ " for austenitic NiMn steel deposit  
 $T = \frac{1}{32}$ " for martensitic cast-iron deposit

If gear travels one direction, hard-surface face of tooth that meshes; if reversing gear, hard-surface both faces.

**B**

FIG. 14-1B. Method of Building up Gear Teeth with Carbon-Steel Welding Rod and Hard-Facing the Wearing Face.



FIG. 14-1C. A Composite Forging Trimmer Die Prepared for Welding. Note the groove that will receive the weld deposit around the die opening.



FIG. 14-1D. The Completed Weld on the Same Trimmer Die, Now Ready for Machining.

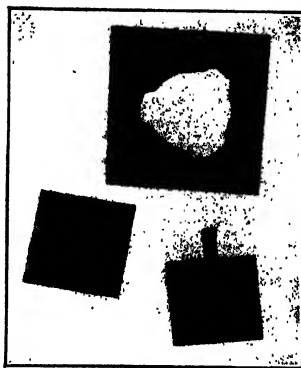


FIG. 14-1E. The Same Punch, Male Die and Female Die after Machining; Ready for Use. These trimmer dies can be restored repeatedly in this manner.

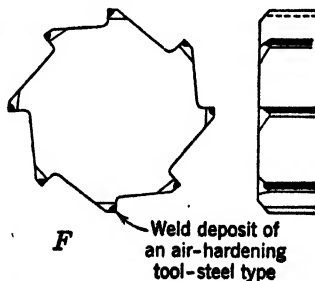


FIG. 14-1F. Method of Making Inexpensive Milling Cutter from Carbon-Steel and Hard-Surfacing Alloy.

thereby saving a large tool-inventory investment. This does not preclude long-run service, but the savings from these may be less impressive.

In the subsequent discussions of materials, hardness and wear resistance receive primary consideration. Other engineering properties that affect service performance are discussed, but engineers may be disappointed by the lack of representative tables of such properties as tensile strength, elongation, and impact strengths, as determined on weld deposits. However, these data might be seriously misleading. The information can be obtained by testing carefully prepared specimens representing the weld metal, but the wide variety of applications, the important influence of welding skill, the trade-name identification of the alloys instead of standard specifications, and the complexity of residual stresses in welded assemblies make utilization of test data fraught with uncertainty from indeterminate variables. Where numerical values are presented, they should be accepted only with the foregoing reservations.

#### HARDNESS

The term hardness<sup>8,9</sup> is difficult to define precisely. It applies generally to the properties that confer resistance to indentation, deformation, compression, cutting, scratching, or abrasion. From these, a correlation with wear resistance would be expected. However, the quality of toughness is also involved; in some cases it may be paramount, as in those where rubber will outwear steel. In other cases, an approximate relationship exists, but, before hardness is used as an index of wear resistance the correlation should be established.

Minerals are commonly reported in terms of scratch hardness, whereas metals are generally tested by indentation methods. Data for comparing the two are therefore useful, though it should be understood that they do not represent identical properties. With this qualification, several tables are included to facilitate approximate conversion from one system to another. As an engineer using these data may be familiar with some but not with the others, a very brief description of each is included.

Mohs's scale of hardness is a method that can be applied in the field, as it involves relative scratch hardness, with ten minerals as standards. The steps are not equal, unfortunately, the difference between no. 9 (corundum) and no. 10 (diamond) probably being as great as that between nos. 1 and 9.

Brinell hardness for steels is obtained from the diameter of the indentation made by a 10-mm ball (hardened steel or cemented tungsten

carbide) under a load of 3000 kg for 30 sec. It is reported as a Brinell hardness number, abbreviated herein as BHN. It is a standard method for testing steels and other metals, but it cannot be used for brittle minerals, such as those in Mohs's scale, because they fracture rather than yield to the indenting ball. Any correlation with Mohs's system must be based on another technique that is applicable to both types of material.

Rockwell hardness is another indentation method widely used for metals. It employs several types of indenters, the most useful of which is a diamond cone, the "Brale." Each combination of load and indenter is designated by a letter. Thus the diamond Brale with a 150-kg load provides C scale values, here abbreviated as Rc. The Rockwell C scale is most applicable to hardened steels and hard-surfacing alloys. Brittle minerals fracture under the indenter, providing invalid results similar to the Brinell test behavior.

A diamond may be substituted for the round ball of the Brinell instrument. If very light loads are applied, an indentation may be obtained without fracture in brittle materials as well as in metals. The small size of such an indentation, which is measured with a microscope, permits reporting of the indentation hardness of the microconstituents of alloys (Fig. 14-2), provided very light loads are employed, whereas the Rockwell and Brinell indentations are so large that only the average hardness of a fine heterogeneous structure can be obtained. The Vickers instrument features a square-base diamond-pyramid indenter, the results of which are reported as Vickers pyramid numbers,\* abbreviated as VPN. The Tukon tester also will accommodate a Vickers indenter.

The Knoop indenter is a diamond pyramid differing from the Vickers type in proportions and depth of impression. It has a length-to-width ratio of 7.11:1.00; the long dimension of an indentation being measured microscopically in practice. It was developed to measure the hardness of very brittle materials and of microscopic areas. The apparent hardness values, reported as Knoop numbers,\* are sensitive to the applied load and tend to rise sharply for very hard materials as the load is decreased. The Tukon tester is commonly employed for Knoop hardness determinations.

The Bierbaum "Microcharacter" is a scratch-hardness instrument for precision measurements. It employs a diamond point, cut as the corner of a cube, that is drawn across the surface to be measured under a load of 3 or 9 grams. The width of the V-shaped scratch is measured

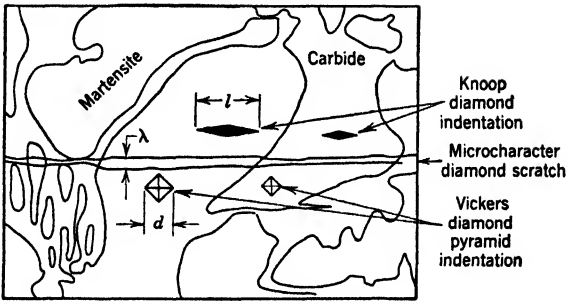
\* Both the Vickers and Knoop hardness values reported herein are based on an applied load of 25 grams.



in microns under a calibrated microscope and converted to hardness numbers that are reported as K values. This type of hardness seems most closely related to abrasive wear.<sup>10</sup> Unfortunately, the instrument is a research tool and is not adapted to shop or field use. The



Constituent	Vickers	Knoop	Micro-character	Re	BHN	Wet-Sand Abrasion Factor
Martensite	362	555	1700 ± }	62	600	0.27
Carbide	965	1080	5000 ± }			



	Microcharacter	Vickers	Knoop
Definition	$K = \frac{L - P}{\lambda^2 - q}$	$VPN = \frac{L}{Ar}$	$I = \frac{L}{Ap}$
Working formula	$K = \lambda^{-2} \cdot 10^4$	$VPN = \frac{1.8544 \cdot L}{d^2}$	$I = \frac{L}{l^2 \cdot Cp}$
$L$ = load in kilograms			
$\lambda$ = width of scratch in millimeters			
$p$ and $q$ = constants of diamond			
$l$ = long diagonal in millimeters			
$Ar$ = recovered area			
$Cp$ = constant relating $l$ to projected area			
$Ap$ = projected (unrecovered) area			
$d$ = diagonal in millimeters			

Fig. 14-2. Microhardness Methods Demonstrated on Ni-Hard Cast Iron. Photomicrograph at 300X.

measurement of the impressions is an exacting and difficult operation. Like the Knoop and diamond-pyramid methods, it can deal with either brittle or ductile materials.

TABLE 14-1. KNOOP HARDNESS OF MOHS'S MINERALS AND ABRASIVE MATERIALS\*

Samples	Knoop Nos.
Gypsum	32
Calcite	135
Fluorite	163
Apatite parallel to axis	360
Apatite perpendicular to axis	430
Albite	490
Orthoclase	560
Crystalline quartz parallel to axis	710
Crystalline quartz perpendicular to axis	790
Topaz	1250
Carboloy	1050 to 1500
Alundum	1620 to 1680
Silicon Carbide	2050 to 2150
Boron Carbide	2250 to 2260
Diamond	5500 to 6950

\* The Knoop Indenter as Applied to Testing Nonmetallic Materials Ranging from Plastics to Diamonds, by V. E. Lysaght, *ASTM Bull.* (Jan., 1946) 138, 39.

TABLE 14-2. RELATIONS BETWEEN MOHS'S SCALE AND MICROHARDNESS NUMBERS \*

Variations in microhardness of the materials are due to variations in texture, impurities, and anisotropy.

Materials	Mohs's Scale	Microhardness	Average by H. C. Hodge & J. H. McKay
Talc	1	0.8- 21.5	1
Selenite	2	10.2- 56.6	11
Calcite	3	126 - 135	129
Fluorite	4	138 - 145	143
Apatite	5	870 -1740	
Orthoclase	6	2100 -2500	
Quartz	7	2066 -3906	2700
Topaz	8	2770 -4444	3420
Corundum	9	3906 -8264	5300

\* As given in Williams', *Hardness and Hardness Measurements*, ASM, 1942, p. 133. Originally published in *Am. Mineral.*, 19, 4 (Apr. 1934).

In Table 14-1 Knoop hardness and in Table 14-2 Microcharacter values are reported in terms of Mohs's scale. These will permit evaluation of the microconstituents of hard-surfacing alloys in terms of the generally available data on minerals. In Fig. 14-2, Knoop, diamond-

pyramid and Microcharacter impressions are shown. Table 14-3 contains values obtained on some of the constituents of hard-weld deposits. Table 14-4 is included for convenience in comparing Brinell and Rockwell C hardness value for ferrous metals.

TABLE 14-3. HARDNESS OF SOME MICROCONSTITUENTS IN HARD-SURFACING WELD DEPOSITS

Constituent	Microhardness		
	VPN,* 25-g Load	Knoop I, 25-g Load	Microcharacter, K, 9-g Load
Ferrite			
In 0.20% C steel	104	154	
Pearlite			
In 1.6% Cr white cast iron	250- 355		
In 1.6% Ni:1.5% Cr white cast iron	314	458	
In 2.1% Ni:2.4% Cr white cast iron			1100-1525
In Ni-Cr white cast iron			772- 865
In 7.6% Cr white cast iron			550
Austenite			
3.9% Mn:3.6% Ni:2.1% Cr white cast iron			370- 590
1.5% C:11.8% Cr steel	353	412	
In Ni-Resist cast iron	165- 243		
Martensite			
In Ni-Hard cast iron	390- 640	506 ±	1200-2500
In Cr-Mo cast iron	473	682	
Cementite			
Iron carbide in gray cast iron	940		
In 1.6% Cr white cast iron	855-1080		
In Ni-Hard cast iron	1052-1800	1108+	2660-9000
In pearlitic white cast iron	1128-1270	1720	
Chromium carbides			
24% Cr white cast iron			5350-7400
1.5% C:11.8% Cr steel	1960		
Cr-Co-W	1672-2520	1720-2220	5730-7570
Chromium boride			
Ni-Cr-B-C	2668	2912	

\* The Vickers pyramid numbers are roughly equivalent to Brinell hardness numbers in the range around 200 BHN, with heavy loads. At higher levels, the values diverge (695 VPN = about 614 BHN). This note is included for the benefit of engineers who are most familiar with Brinell hardness, with the caution that there is no precise equivalency, especially at low loads, although the mathematical bases are comparable.

## ABRASION

Abrasive wear is usually the result of scratching. It is most frequently caused by nonmetallic materials. Abrasion may be produced by processed minerals, as in crushing, digging, and grinding activities; by oxidation products, as in dry wear (iron oxide is a hard and efficient abrasive); by foreign particles in a lubricant, as in the case of air-borne sand and grit in the oiling system of an automobile; or by deliberate application, as in commercial grinding, honing, and lapping operations. In general, a substance is seriously scratched only by materials harder than itself. Most protection against abrasion attempts to employ this

principle. It is not always valid, perhaps because even nominally pure substances may contain harder foreign particles, or because there are additional factors that are little understood or unknown. Rubber provides an interesting exception where toughness or elasticity appears much more important than hardness in many applications.

TABLE 14-4. APPROXIMATE CONVERSION FROM ROCKWELL C SCALE TO BRINELL HARDNESS NUMBERS

Rockwell C	Brinell	
	Steel	Ni-Cr Cast Iron
45	444	380
46	461	390
47	469	400
48	477	412
49	495	425
50	504	438
51	514	452
52	534	466
53	545	482
54	555	500
55	566	517
56	578	534
57	601	552
58	614	572
59	627	592
60	640	616
61	653	640
62	667	666
63	682	685
64	697	705
65	712	720

Some forms of abrasion involve little or no impact, but others permit the kinetic energy of a blow to play an important role. Although wear in the ordinary sense does not result from stresses sufficient to cause fracture, in practical applications a brittle material may have its useful life terminated by a sudden blow. Thus martensitic cast irons are known to be very wear-resistant in crushing and grinding operations, but the impact conditions of service force the selection of some tougher abrasion-resistant material. The wide acceptance of austenitic manganese steel is partly due to its toughness and ability to absorb impact stresses without damage. It has good abrasion resistance under many circumstances, but there are applications where it wears at a more rapid rate than the harder cast irons. Despite this,

it is repeatedly selected, chiefly because it provides an insurance against fracture and premature failure probably greater than that of any other wear-resistance metal.

Impact may cause failure on a smaller scale also. The shear stresses under a point or an edge that has been applied with a blow are quite large. They can easily exceed the elastic strength of the material struck, which, if brittle, then shatters readily. Extreme brittleness, as of glass that contains high residual stresses, or where a perfect cleavage is coupled with high hardness, is favorable to this type of failure, which may simulate erosion rather than fracture if it occurs on a microscopic scale. Shot or sand blasting may be accompanied by this factor as well as by the scratching of abrasive particles. Yielding of the surface by either elastic deformation or by plastic flow tends to relieve these stresses and prevent fracture. A fine-grained structure may also minimize failure and consequent wear by localizing cleavage cracks in microscopic crystals rather than permitting them to be propagated across a large grain. The greater resistance to impact abrasive wear of flint in comparison with quartz or of molded versus massive crystalline boron carbide may tentatively be attributed to such a mechanism.

Metallic substances and intermetallic compounds, even when they are brittle by engineering standards, probably owe their superior wear resistance to some ductility, which in combination with great strength provides toughness considerably above that of most minerals and ceramic substances. The qualitative difference between such materials can be easily demonstrated by an attempt to measure the penetration hardness of a brittle mineral, such as quartz, by means of a diamond cone (the Rockwell hardness test). The mineral will fracture, whereas a piece of the most brittle cast iron (if reasonably large in size) will yield and permit the hardness determination. This hypothesis explains partially why hardness alone is not a reliable index of wear resistance.

Resistance to wear that involves heat checking, as in frictional braking, is also influenced by brittleness. Here the stresses are the result of temperature gradients rather than the kinetic energy of impact, but the capacity to absorb the stresses is similarly aided by plasticity. A metal with a low modulus of elasticity, such as gray cast iron, is generally considered more resistant to thermal cracking than a hard white iron, though its ability to withstand frictional wear may not be so great. The low modulus is associated with lower stresses for a given amount of thermal expansion. The greater plasticity of gray

irons, coupled with their lower moduli, provides an explanation of their popularity in brake service, particularly as brake drums.

#### ABRASION TEST TECHNIQUE

The wet-sand abrasion factors reported herein were obtained with a machine (Fig. 14-3) described by H. N. Blake <sup>11</sup> in 1928, but with considerably modified technique. The essential parts of the apparatus are a lap, a trough for abrasive, arms for holding the specimens and for applying uniform and measured pressure, a hydraulic classification system for removing fines, and mechanism for dragging the test specimen over the lap, which is a flat circular copper track about 2 in. wide and 4 ft in diameter. The standard abrasive consists of 40 lb of quartz sand with a grain fineness number of 50, mixed with 30 quarts of water. Test pieces with a wearing face  $1\frac{1}{2}$  in. by  $2\frac{1}{4}$  in. are held against the lap with a spring pressure of 38.5 psi while being moved at the rate of about 119 ft per minute for a total distance of 1.35 miles.

Before each test, the specimen under investigation is worn in against a track until it has completely conformed to the minor irregularities in surface contour. It is then carefully cleaned, dried, and weighed, after which the test is begun on two specimens, the second of which is of annealed SAE 1020 steel. Inclusion of this readily duplicated material provides a standard that will indicate any serious departure from the correct testing conditions. The final report of wear is given in terms of weight loss in comparison with the standard, thus reducing the data for many materials to a common denominator. The relative ranking of several interesting engineering alloys and metallographic structures appears in Table 14-5.

With the present standardized procedure, excellent reproducibility is obtained as evidenced by duplicate tests. As calculated by statis-



FIG. 14-3. Abrasion-Testing Device from Which the Wet-Sand Abrasion Factors Reported Herein Were Obtained.

tical methods,<sup>12</sup> the correlation coefficient (Pearson product moment) between duplicate tests is 0.97. The reliability of the average of *two* such tests would be 0.985; a correlation of unity (1.00) is said to indicate perfect reliability and one of zero (0.00) its complete absence. The standard error (S.E.) of a single determination is 0.028; of the average of two tests, 0.020. Theoretically, this implies that a second duplicate determination will be within plus or minus this standard error approximately two thirds of the time, or, in other words, two thirds of such test values should fall within  $\pm 1$  S.E., practically all ( $99 \pm \%$ ) within  $\pm 3$  S.E. For those more accustomed to dealing with probable error (P.E.),  $P.E. = 0.6745 \times S.E.$  These correlations are based on uniform materials. The agreement between duplicate tests on weld deposits is usually poorer because of nonuniformity in the specimens.

TABLE 14-5. TYPICAL WET-SAND ABRASION FACTORS

Material	Hardness, BHN	Abrasion Factor
Ferritic (Armco ingot iron)	90	1.40
Gray cast irons	200 $\pm$	1.00-1.50
SAE 1020 steel (standard)	107	1.00
White cast irons (pearlitic)	400 $\pm$	0.90-1.00
Alloy white cast irons	400-600	0.70-1.00
Pearlite (0.85% C steel)	220-350	0.75-0.85
Austenite (12% Mn steel)	200	0.75-0.85
Bainite	512	0.75 $\pm$
Martensite	715	0.60 $\pm$
Martensitic cast iron (Ni-Hard)	550-750	0.25-0.60
Cemented tungsten carbide		0.17

A somewhat similar test has been employed by Weiss<sup>13</sup> to rank a large number of steels. The data, which were obtained with silicon carbide as an abrasive on a cast-iron lap, are summarized in Table 14-6, which may be useful if such steels are substituted for more conventional hard-surfacing alloys.

Both the tests mentioned involve a loose abrasive. It seems reasonable to expect that different results would be obtained if the abrasive were fixed, as would be the case with the bonded and anchored grit of a grinding wheel. In the latter case, the abrasive could not selectively wear away the softer part of a composite structure and thus undermine harder and more resistant particles, but would, of necessity, have to cut them away slowly. A test with bonded abrasive would thus appear more favorable to such heterogeneous structures as austenitic cast irons, which have very hard carbides set in a much

softer matrix. Qualitative confirmation of this has been obtained from a comparison of wet-sand abrasion factors with machine grinding rates. No thorough investigation of the wear of hard-surfacing materials against standardized anchored abrasives is available, however.

TABLE 14-6. RELATIVE ABRASION BY WET SILICON CARBIDE

Adapted from Data by Weiss<sup>13</sup>

Material	Brinell Hardness Number	Abrasion Factor, Weight Loss of Sample Weight Loss of Standard
Soft gray iron	150	3.30
Phosphor bronze	52	2.65
Gray cast iron	190	1.97
Manganese bronze	107	1.82
Aluminum bronze	101	1.29
SAE 1010 steel (standard)		1.00
Armco iron		0.96
SAE 1025 steel	149	0.88
SAE 1040 steel	156	0.81
SAE 3130 steel	183	0.80
SAE 5140 steel	163	0.80
Stainless (0.12% C:13% Cr) steel	241	0.75
Stainless (0.30% C:14% Cr) steel	241	0.70
SAE 1040 steel	270	0.70
SAE 5150 steel	217	0.69
SAE 3140 steel	196	0.68
Stainless (0.12% C:13% Cr) steel	460	0.61
White cast iron	380	0.55
SAE 3130 steel	460	0.54
SAE 3140 steel	555	0.51
Stainless (0.30% C:14% Cr) steel	627	0.48
Carburized SAE 1020 steel	680	0.47
Work-hardened austenitic Mn steel		0.42
SAE 5140 steel	600	0.42
Carburized SAE 5120 steel	712	0.42
SAE 5150 steel	627	0.40

The most common basis for approximately predicting wear resistance is probably a measurement of hardness. However, hardness may be quite misleading and should be relied on only in the absence of other evidence. This will frequently be the case. The engineer should be especially cautious in comparing two materials of quite different nature on the basis of hardness.



The role of abrasive hardness requires examination. Although the puzzling occurrence of wear on a hard object from contact with a much softer substance has been observed<sup>14</sup> occasionally, it should not prevent consideration of relative hardness. If the characteristics of the wearing agent are known and it is possible to select a hard-facing alloy of superior hardness, a prediction of good service performance is reasonable. With mineral substances the hardness values on Mohs's scale that are included in any standard test on mineralogy<sup>15</sup> are useful. For comparison, a rough correlation with metallurgical hardness scales is included in Table 14-7.

TABLE 14-7. HARDNESS COMPARISONS \*

Mohs's No. (1)	Mineral Equivalent (2)	Knoop No. (3)	VHN (4)	BHN (5)	Rockwell (6) B C	Micro-character (7)	Steel Equivalents
1	Talc	....	.....	...	.. ..	1- 21	
1.5							
2	Gypsum	32	30	30	20 ..	10- 57	
2.5							
3	Calcite	135	135	135	75 ..	126- 135	Ferrite (8)
3.5							
4	Fluorite	163	160	160	85 3	138- 145	Spheroidite (9)
4.5							Coarse pearlite (9), austenite (8)
5	Apatite	430	430	410	.. 43	870-1740	Fine pearlite (9), coarse bainite (9)
5.5							Fine bainite (9)
6	Orthoclase	560	560	510	.. 52	2100-2500	
6.5							Martensite (8)
7	Quartz	790	790	640	.. 61	2070-3900	
7.5							Iron carbide (8)
8	Topaz	1250	<1250	...	.. ..	2800-4400	Complex alloy carbides (8)
8.5							Complex alloy carbides (8)
9	Corundum	3000	<3000	...	.. ..	3900-8300	
9.5							
10	Diamond	8000	<8000	...	.. ..	.....	

\* This comparison of the Mohs's mineral scale and Microcharacter scratch scale with the common indentation scales for metals should not be considered a table for conversions, since the individual hardness methods are arbitrary and do not measure the same combination of properties. Conversion from one indentation scale to another is in itself very approximate and generally is not considered reliable except for purposes of making rough estimates of hardness level in terms of the hardness scale to which the conversion is made.

(1) Estimation of Mohs's scale hardness is generally restricted to 0.5 of a scale point.

(2) Minerals used by Mohs to establish the original scale.

(3) Knoop hardness measurements of the Mohs scale minerals presented in Hoyt's *Metals & Alloys Data Book*, p. 7.

(4) From Knoop according to conversions given in *Trans. ASM*, **33** (1944), 134.

(5) From VHN according to conversions, for steel ball, given in Williams' *Hardness & Hardness Measurements*, p. 462.

(6) Same as (5).

(7) Microcharacter hardness measurements of the Mohs scale minerals given in Williams' *Hardness & Hardness Measurements*, p. 133.

(8) Related to Knoop hardness; unpublished data of the American Brake Shoe Company.

(9) Related to Rockwell C hardness; data presented by M. Gensamer, *Trans. ASM*, **80** (1942), 983.

Caution in judging mineral hardness is advised. The important abrasive agent may be concealed from casual observation. Thus limestone, which is softer than the martensite of hardened steel, may contain siliceous areas or quartz inclusions whose hardness considerably exceeds that of martensite. The harder substance will probably be the determining factor in service behavior.



600×

FIG. 14-4. Good Structure for Wet-Sand Abrasion Resistance.

Martensitic White Cast Iron (Ni-Hard)

Chemical Analysis

C%	Ni%	Cr%
3.18	4.58	1.39

Constituents: Very hard carbides (white) and martensite (acicular).

Wet-Sand  
Abrasion

Rc	BHN	Factor
63	713	0.30



300×

FIG. 14-5. Poor Structure for Wet-Sand Abrasion Resistance.

Pearlitic Gray Cast Iron

Chemical Analysis

C%	Ni%	Cr%
3.02	0.95	1.43

Constituents: Graphite flakes in a pearlite matrix. The pearlite alone (which consists of alternate lamellas of iron carbide and ferrite) has an abrasion factor of about 0.80, but the presence of the graphite increases it to about 1.20. Hardness: 217 BHN.

A similar complication is encountered in abrasion-resistant metals. In heterogeneous structures, such as cast irons, the various constituents may differ widely in hardness, ranging from soft graphite, which is detrimental to abrasion resistance, to very hard carbide. Also, the matrix in which the hard particles are imbedded may be a controlling factor. Conventional hardness tests, such as the Brinell or Rockwell, provide an average hardness, masking the effect of both hard and soft constituents.

TABLE 14-8. SUMMARY OF HARD-SURFACING ALLOYS  
Arranged in Order of Wet-Quartz-Sand Abrasion Resistance

Chemical Analysis

	C%	Mn%	Si%	Ni%	Cr%	Mo%	W%	Co%	B%	V%	Weld Type	Wet-Sand Rc BHN	Abrasion Factor
	Mosaic of cemented tungsten carbide insets (Fig. 14-10)												
D	3.65	1.24	1.12				4.61				Gas	60	0.17
D											Gas	58	0.32
D											Gas	67	0.36
D											Gas	58	0.40
D	3.65	1.24	1.12				4.61				Arc	64	0.40-0.45
R											Arc	62	0.41-0.53
D											Gas	62	0.41
D	Nominal.*				7-11	12-16			1-2		Gas	58	0.42-0.44
R	3.02	0.31	0.91		4.02	6.22	2.05				Gas	627	0.42
D	3.83	1.84	1.20			7.16					Arc	60	0.43
D											Arc	58	0.45
D											Arc	64	0.47-0.53
D											Arc	64	0.47
R	3.17	0.64	0.87		1.85						Gas	56	0.47
R	2.67	1.56	0.89		30.9						Gas	56	0.47
R	2.62	3.62	1.02		31.8						Gas	56	0.49
R	3.71	0.15	0.63		7.44						Arc	512	0.50
R	3.48	0.26	1.19		8.09	1.82	14.0	45.5			Arc	60	0.51
R	0.72	0.64	1.26		4.32	2.98	14.88	43.1 (Fig. 14-13)			Arc	60	0.52
R	3.75	0.12	0.84		7.53	7.10	4.82				Gas	61	0.53
D	3.19	0.20	1.24		7.61	2.04 }					Arc	61	0.53
R	3.16	0.20	0.81		4.27	4.21					Gas	60	0.53
R	3.60	2.64	2.07		15.54	8.93 (Figs. 14-25, 14-26, 14-27)					Arc	67	0.54-0.59
R	5.28	0.21	2.32		8.51	8.51					Arc	65	0.54
R	3.72	1.96	1.68		9.15	1.83					Arc	62	0.54
R	3.83	1.84	1.20		7.16						Arc	62	0.54
R	1.29	0.51	0.76		4.83	8.70	1.97				Arc	59	0.54
R	2.67	1.56	0.89		30.86		14.0	45.5			Gas	56	0.54
R	3.85	1.24	1.12								Arc	61	0.55
D											Gas	59	0.55-0.57
D	1.24	1.63	1.23		27.48	4.03					Gas	53	0.57
D											Gas	53	0.58-0.62
D	Martensitic steel										Arc	61	0.59
R	3.52	3.02	1.89		6.34	1.73					Arc	600	0.59
R	2.62	3.62	1.02		31.76						Arc	59	0.60
R	3.57	1.72	1.61		8.34	2.08					Arc	47	0.60
D											Arc	59	0.61-0.62
D	Martensitic steel										Arc	600	0.61
R	2.60	3.50	1.00		31.68	1.93					Arc	58	0.61
R	3.71	0.14	1.17		7.05						Arc	58	0.61

R	2.11	0.80	0.73	1.25	2.41	3.79	Gas	38	0.61
R	3.16	0.20	0.81	4.27	4.21	4.21	Gas	60	0.62-0.63
R	3.16	0.35	1.91	3.45	4.02	4.02	Gas	63	0.64
R	3.82	0.20	0.81	6.94	1.55	1.55	Arc	59	0.64
R	Nominal:*			7-11	12-16	12-16	Arc	63	0.65-0.73
R	3.07	0.18	0.88	3.87	1.27	7-11	Arc	59	0.66
R	3.75	0.12	0.84	7.53	2.04	2.04	Arc	60	0.66
D	3.19	0.20	1.24	7.61	2.04	2.04	Arc	57	0.66
R	3.87	1.40	1.02	2.17	2.17	2.17	Arc	43	0.66
R	1.06		2.12	28.33	5.25	61.0	Arc	63	0.67-0.77
R	0.89	0.88	1.53	4.15	6.97	5.13 (Hi-Speed)	Gas	62	0.67
R	0.72	0.64	1.26	4.32	7.10	4.82 (Steel type)	Arc	55	0.67
R	3.55	1.85	1.19	11.54	4.61		Arc	53	0.67-0.78
R	3.85	1.12	1.12				Arc	47	0.67
R	0.85	0.20	0.14	0.01 }			Arc	60	0.69
D	1.11	0.18	0.86	7.05 }	8.61		Arc	56	0.69
R	4.21	0.21	0.89	16.06	1.93		Gas	55	0.69
R	3.71	0.14	1.17	7.05			Gas	55	0.69-0.74
R	3.63	1.92	1.42	10.58			Arc	57	0.70
R	3.55	1.85	1.19	11.54			Arc	55	0.70
R	3.07	0.18	0.88	1.27			Gas	55	0.70
R	2.98	3.81	1.39	11.77			Gas	51	0.71
R	2.64	1.52	0.89	30.71			Gas	54	0.71-0.73
R	1.27	0.76	0.69	5.87			Gas	52	0.71
R	1.52	0.46	0.69	3.91			Gas	58	0.73-0.76
R	3.59	1.87	1.07	7-11			Arc	63	0.73
R	Nominal:*			12-16			Arc	36	0.73-0.76
R	1.52	0.46	0.69	3.91			Arc	58	0.73
R	0.13	0.44	0.02	0.13			Arc	58	0.74-0.76
D	0.89	0.57	0.73	0.20			Gas	60	0.74
R	3.82	0.43	1.10	11.74			Arc	42	0.74
R	3.82	0.43	1.10	7.56			Arc	55	0.75
R	1.45	0.39	0.75	4.71			Arc	67	0.76-0.78
R	3.59	1.87	1.07	8.83			Arc	55	0.77
R	1.00	0.65	0.38	5.50			Arc	57	0.78
D	0.46	0.21	0.30	4.11			Arc	44	0.77
R	0.81		0.75	4.0			Arc	42	0.77
R	1.45	0.39	0.75	4.71			Arc	40	0.77
R	0.95		0.75	4.0			Arc	36	0.77
R	0.95		0.75	4.0			Gas	54	0.79-0.81
R	2.19		1.55	27.33			Gas	60	0.79-0.81
R	3.33	2.16	1.59	11.76			Gas	27	0.80
R	1.28	0.62	0.85	6.85			Arc	196	0.80-0.85
R	0.62	0.63	0.19	1.00					
R		13.2		3.97					

TABLE 14-8. SUMMARY OF HARD-SURFACING ALLOYS (Continued)  
Arranged in Order of Wet-Quartz-Sand Abrasion Resistance

Chemical Analysis											Wet-Sand Re BHN	Abrasion Factor
C%	Mn%	Si%	Ni%	Cr%	Mo%	W%	Co%	B%	V%	Cu%		
R 3.64	0.16	1.85		7.42	1.86					0.18	58	0.82
R 0.80	14.01	0.77			0.22							
D 0.65	12.78	0.53			0.17							
R 0.65	12.8	0.53			0.17					0.08	18	0.82
R 3.25	2.20	1.36									217	0.82
R Fe + Si + C = 10% max.												
R 3.88	1.97	1.42										
R 3.92	1.93	1.16										
R 0.64	13.0	0.44									61	0.83
R 0.13	0.44	0.02	0.13								61	0.86
D 0.89	0.57	0.73	0.20						0.31		627	0.85-0.86
R 0.80	14.01	0.77							0.25		56	0.86-0.90
R 0.66	12.5	0.77								0.10	59	0.86
R 2.82	0.20	0.86									223	0.86
R 1.41	1.83											
R 0.95												
D 0.20	0.45	0.07	70.0								36	0.86
R 3.87	1.40	1.02									21	0.86
R 1.06		2.12										
R 1.04	3.52	1.59									187	0.87-0.92
R 5.50	0.34	2.86									56	0.89-0.91
R 3.83	1.84	1.20									50	0.92
R 2.19		1.55									60	0.95-1.00
D 0.95												
R Nominal:*											107	1.00
R 2.19											52	1.02
R 1.41											50	1.03
R 1.04	3.68	1.83									48	1.03
R 0.67	14.6	1.11									62	1.04
R 1.04											47	1.05
R 1.04	3.52	1.59									42	1.08
R 3.04	0.87	3.33									46	1.11
R 3.08	0.70	3.27									31	1.16
R 1.52	0.46	0.69									56	1.17
D 1.08	0.44	0.70									53	1.17
R 2.92	1.10	3.70									43	1.21
R 1.41											47	1.21
R 1.04											344	1.21-1.22
R 1.04	3.52	1.59									228	1.22-1.29
R 3.04	0.87	3.33									48	1.23
R 3.08	0.70	3.27									39	1.38
R 1.52	0.46	0.69									25	1.44
D 1.08	0.44	0.70									161	1.51-1.62
R 2.92	1.10	3.70									286	1.69

\* Nominal composition reported in absence of chemical analysis.

R = chemical analysis of rod.

D = chemical analysis of deposit.

Table 14-8 lists many abrasion factors on weld deposits, which were obtained as part of a broad research program investigating abrasive wear. The factors have been listed in order of merit, the lowest, being the best for this type of abrasion, appearing at the head of the table. It may be noted that some materials appear in several places in the table, with different factors. This reflects the variability of structure in different weld deposits even when made from the same welding-rod alloy.

#### GALLING RESISTANCE

The type of wear or surface deterioration known as galling is quite distinct from abrasion. It is due primarily to welding rather than to scratching and is attributed to the forces of atomic attraction.<sup>16, 17</sup> Atoms of the same or very similar metals cling to each other powerfully, accounting for the tensile strength of materials. The forces decrease rapidly with distance, however, and, when the separation is greater than a millionth of an inch, they are probably negligible. If two clean surfaces of the same metal actually touch each other, they will weld together, evidencing this atomic attraction. Even with apparently smooth surfaces, however, the actual contact points are few under ordinary circumstances, and the effect is not obvious. The thinnest films of oil, dirt, or adsorbed moisture may maintain separation above the critical distance. With carefully smoothed faces, removal of films and dirt by friction, pressure sufficient to break through any residual separating material and to facilitate intimate contact by elastic or plastic deformation, and favorable combinations of adjacent metals, the power of atomic attraction becomes apparent, and seizing or welding takes place. High temperatures, because they soften metals and make plastic flow easier, facilitate this welding but are not necessary.

If small areas "seize," but relative motion is not thereby prevented, pieces of the opposite face may be pulled out. The resultant projection then may cause scoring or excessive local wear, and in the case of moving machine parts serious damage can result. This type of wear and complete stoppage by seizure, which may sometimes be associated with it, can sometimes be prevented by the judicious application of thin layers of hard-surfacing material. The most important characteristic of the deposit is believed to be high compressive strength, as evidenced by hardness. If pressure produces little plastic flow, the actual area that may be forced into contact by heavy pressures will remain

small, the coefficient of friction will probably be low, and the tendency to seize will be minimized. Some advantage is obtained by using dissimilar metals for contact, but this is believed to be secondary to the important requirement of high strength. Those metals that have relatively low yield strengths, such as the austenitic stainless steels or low-carbon irons, are especially likely to gall when surfaces are forced into close contact by heavy pressure.

Service applications that involve the possibility of galling should be examined for hard-surfacing opportunities, and, in general, a very fluid welding rod that will permit a thin, smooth, and very hard deposit should be selected. Hot hardness may also be advantageous if there is little opportunity for lubrication. Martensitic cast irons usually will provide the most economical resistance to galling. It should be noted that in the absence of lubrication the friction between wearing faces may produce very high temperatures. If the alloy is sensitive to this heat, it may be softened and the characteristics of the weld deposit changed markedly. This will be especially true if martensite is produced by the use of nickel. Moderately good hot hardness is achieved when chromium, molybdenum, tungsten, and cobalt, as typified by such compositions as high-speed steel, are employed for hardening. In extreme cases, the cobalt-base alloys that contain little iron probably provide the best protection where frictional heat may reach very high levels.

Frictional braking involving energy absorption is somewhat different. A very hard brake surface would probably cut or wear the opposite member, which is frequently undesirable. Pearlitic gray cast iron, providing good metal-to-metal wear resistance coupled with graphite flakes for lubrication and antigalling properties, is a reasonable choice. It might be employed for emergency surfacing of a brake drum, for example. Such an application of gray cast iron is one of the infrequent cases where this material may be appropriate as a welded facing.

#### MATERIALS FOR HARD SURFACING

Almost any metal or alloy that can be melted and cast may be utilized in the form of welding rod. This provides an embarrassing wealth of possibilities. From the most useful of these a number have been generally selected for commercial exploitation as hard-surfacing materials under dozens of trade names. Hundreds of others cover the multitude of engineering steels and nonferrous alloys. This makes especially difficult the selection of material in the complex and com-

position sensitive grades. Manufacturers' recommendations provide a guide but no guarantee of optimum structure. Some attempts to develop standards or specifications have been made, with unsatisfactory results. It is very unlikely that they can be formulated until a much larger assortment of validated wear tests than are now available can be evolved. If hardness alone is specified, a few service needs will be met, but the majority of applications will be disappointing.

Our customary classification<sup>1, 2, 18</sup> of hard-surfacing alloys groups them on the basis of composition, including as types (a) low-alloy cast irons, (b) alloy steels, (c) alloys containing from 50 to 80 per cent iron, (d) nonferrous alloys, (e) very hard refractory carbides, such as tungsten carbide, that must be sweated to the base or set in a matrix of lower-melting material, and (f) composite rods that melt down to a mixture of tungsten carbide fragments in a matrix, which may itself be a hard-surfacing alloy. The last two are, of course, closely related.

An implied, or sometimes stated, characteristic of this classification is an increase in merit, or wear resistance, in progressing from type (a) toward type (f). This is sometimes true, but it is considered an unsatisfactory generalization. Experience, especially with controlled abrasion tests, has developed so many exceptions that a somewhat different classification is employed in this discussion.

Metallurgical research has generally established that the constitution and structure of metals are fundamental factors that determine their properties. The science of metallography or physical metallurgy has developed around this trend. Composition, as determined by chemical analysis, is important and may be decisive in the production of a desired structure with its attendant properties, but other factors, such as heat treatment, may be more influential. It is also possible to produce a required structure with several different compositions or to produce several structures by different treatments of the same alloy. For these reasons it is desirable to classify hard-surfacing deposits in terms of structure where possible.

## WELDING METHODS

The methods of weld deposition are worthy of further comment, as they differ somewhat in their influence on the resulting deposits. Most of the inexpensive welding rods available produce melts that are essentially alloy steels when solidified. An astonishing range of properties can be developed in such steels by heat treatment. Although controlled heat treatments are seldom intentionally applied to weld deposits, the *cooling of the weld* after solidification constitutes a heat treatment that



cannot be neglected; indeed, with a single typical cooling cycle it is possible to produce by adjustment of alloy and carbon content almost the entire gamut of structures in weld deposits that is developed in



FIG. 14-6. Electric Melting Furnaces for Manufacture of Hard-Surfacing Welding Rods. The induction furnaces in the foreground provide a means for precise analysis control of critical alloys, while the arc furnace, by means of its slag, permits metal refinement and removal of undesirable elements.



FIG. 14-7. Dipping Hard-Surfacing Rods to Provide Them with a Suitable Flux Coating.



FIG. 14-8. Pouring Cast Welding Rods. Each flask contains a number of rods fed from a common gate. Sometimes metal permanent molds are used.

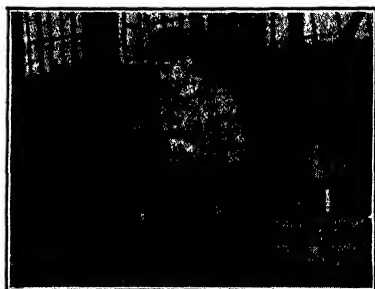


FIG. 14-9. Extrusion Coating of Welding Rods for Electric Welding.

alloy steels by various heat treatments. Thus, the *cooling rates* of welds, as influenced by deposition technique, are important.

The electric arc is the most intense readily available source of heat. The speed with which it can melt a rod to permit its alloying with the base metal is a significant characteristic. Arc welding is usually

selected as the most economical method of deposition; cooling rate being seldom considered. The very rapid heat input is associated with restricted local heating and comparatively rapid cooling. This effect is maximum when small-diameter welding-rod electrodes are employed. Thus, *electric-arc deposits cool rapidly*, and *arc welding with small rods is indicated where minimum heating of the parent metal is required*. Low welding current is a similar factor. Certain applications, such as the repair welding or hard facing of heat-treated austenitic manganese steel, require minimum local heating to avoid serious embrittlement of the underlying base metal.

The intensity of the electric arc usually results in fusion of a superficial layer of the parent metal. This mixes with the weld deposit and modifies its composition and perhaps its ultimate structure. If rods intended for gas welding are employed as electrodes or if a manufacturer has not properly balanced the electrode composition to compensate for this mixing or dilution effect, unexpected or adverse effects may be obtained. It should be noted that proper balancing, if it has been done, can only allow for average deposition conditions and cooling rates; thus departure from manufacturers' recommendations should be avoided unless it is known or suspected that the balance between composition and cooling rate is wrong.

The oxyacetylene flame is less intense than the arc, but with it more control over heat input and cooling rate is possible. The preheating that is practicable tends to minimize thermal gradients adjacent to the weld. As such gradients are frequently the source of serious stresses that may crack the weld or the base metal, successful gas welding may sometimes be possible when arc welding is out of the question.

Even if preheating is not intentional, the slower rate of heat input from the gas flame permits the base metal to absorb a larger proportion of the total heat applied before fusion occurs. This extra heat retards cooling to such an extent that *gas welds characteristically cool more slowly than arc welds*. This, of course, affects structure and properties. Where critical slow-cooling rates are required for optimum properties, as with certain martensitic irons and steels, oxyacetylene welds may be superior in service performance because of this factor.

The flame of a welding torch produces its heat by chemical reactions; the hydrocarbon gas and the oxygen that contribute must be considered from the perspective of other reactions also. The torch operator can make the flame either oxidizing or reducing at will. Most welding is probably best done with the neutral flame that is the balance between these two. If an excess of oxygen is permitted, metal oxides can form

by reaction with the deposited metal; these may dissolve in the melt and react with any carbon present to form carbon monoxide gas just before or during solidification, which is evidenced by gas bubbles or blowholes in the weld deposit. Such deposits usually have inferior abrasion resistance, and the contributing conditions should be avoided. As a precisely neutral flame may be difficult to achieve, a slightly reducing flame is generally recommended.

If an excess of hydrocarbon is present, as witnessed by a yellow or very luminous flame, it may cause carbon to dissolve in the melt and raise its carbon content. The desirability of this is determined by circumstances; carbon frequently increases abrasion resistance and thus may be beneficial, but toughness and impact resistance may be simultaneously lowered. Weld deposits containing strong carbide-forming elements such as tungsten, molybdenum, vanadium, tantalum, columbium, and chromium are very likely to absorb carbon.

#### WELDING-ROD MANUFACTURE

The manufacture of hard-surfacing welding rods influences their cost considerably. If the composition is such that it has a parallel in the field of commercial wrought alloys and can be readily drawn into wire, the cost to the consumer may be relatively low, especially as such types usually are low in alloy content. If the rod is for electric welding, a flux coating adds appreciably to the cost of production.

As the proportion of alloys increases, drawing usually becomes more difficult and with carbon above certain limits becomes commercially impractical. Since carbon is an important element for conferring abrasion resistance, this makes the best materials for such service inherently more expensive. The brittle high-carbon alloys are generally cast; that is, each welding rod is an individual casting. These may be used bare for oxyacetylene welding but are usually flux-coated for arc deposition.

The flux coating<sup>2,19</sup> contains a number of materials for such purposes as arc stabilization, protection of the molten weld metal from oxidation, deoxidation of the deposit, fluxing of impurities, thermal and electrical insulation, and control of metal transfer. The arc being similar to a tiny electric furnace, it is possible to include coating ingredients that will alloy with the rod metal to produce a deposit considerably different from the rod in composition. Certain composite rods take advantage of this; the rod itself being of inexpensive low carbon steel and the coating containing the alloying elements. Deposits

from such composites may approach the properties of those from homogeneous rods, when made under perfect welding conditions, but the presence of electric steel-making variables under only casual control tends to make the resulting metal rather uncertain in composition and performance. In Table 14-9 are presented three examples of composite rod composition, with chemical analyses of resulting specimen

TABLE 14-9. COMPOSITION AND PERFORMANCE OF THREE SPECIMEN COMPOSITE WELDING-ROD TYPES

Type	A		B		C	
Steel Portion	Sheath or Tube		Soft Steel Wire		Soft Steel Wire	
Alloys	Tube Filling Ferrochromium, Ferrosilicon, Ferromanganese, Graphite, etc.		Flux Coating Ferrochromium, Graphite, Man- ganese Dioxide, Silica, etc.		Flux Coating Ferrochromium, Manganese Di- oxide, Silica, Graphite, etc.	
Analysis of	Tube	Filling	Core	Coating	Core	Coating
C%	0.12	4.85	0.21	4.22	0.18	2.047
As graphite:	.....	1.40	.....	2.93	.....	0.20
Mn%	0.37	23.15	0.50	19.15	0.49	16.6
Si%	0.02	7.20	0.02	6.23	0.02	6.90
Cr%	0.01	41.40	0.01	32.40	0.01	37.83
Fe%	99+	22.20	99+	14.66	99+	15.10
	Electric Weld		Electric Weld		Oxyacetylene Weld	
	Deposit		Deposit		Deposit	
C%	0.60		0.64		1.45	
Mn%	2.41		4.27		2.78	
Si%	0.40		0.96		0.24	
Cr%	6.02		13.04		12.14	
Fe%	90.1		79.9		82.9	

Test Results on Each of 4 Individual Weld Deposits

Specimen	Wet-Sand			Wet-Sand			Wet-Sand		
	Hardness	Abrasion	Factor	Hardness	Abrasion	Factor	Hardness	Abrasion	Factor
	Rc	BHN		Rc	BHN		Rc	BHN	
1	41	$\frac{340}{444}$	0.83	31	$\frac{302}{377}$	0.99	37	$\frac{286}{302}$	0.74
2	42	332	0.86	30	$\frac{286}{302}$	0.88	36	$\frac{255}{340}$	0.92
3	48	387	1.07	34	$\frac{286}{302}$	0.97	44	$\frac{364}{477}$	0.88
4	46	321	0.80	35	$\frac{302}{311}$	1.08	36	$\frac{277}{302}$	0.88
Average	44	417	0.90	33	303	0.98	38	325	0.88

weld deposits and the range in hardness and abrasion resistance encountered in a survey of four separate weld test specimens from each type of rod.

Some welders do not hesitate to remove the flux coating, which is rather brittle and easily cracked off, from an arc-welding electrode in order to obtain a bare rod for oxyacetylene deposition. The possible importance of the coating to final weld composition may be inferred from Table 14-8. Anyone aware of this can justify the insistence that torch welding be done with rods specifically intended for such service, whether they are provided with or without a coating. Even less justifiable is the prejudice of some welders for bare rod in arc welding, which leads to coating removal as a routine, regardless of job requirements. This should be avoided by close supervision.

The influence of carbon in conferring improved abrasion resistance may be seen in Table 14-9. Some carbon may be absorbed from the gas flame; in general, the arc causes a corresponding loss, and the resultant deposits are usually lower in abrasion resistance than similar gas welds. This loss can be accentuated by welding with a long arc.

#### METALLIC CARBIDES

Standing at the top in wear resistance are the very hard intermetallic compounds, such as tungsten carbide, boron carbide, columbium and tantalum carbides, and aggregates containing these. Chromium carbides should perhaps be included, though they are usually present as microconstituents. Iron carbide appears to be inferior in toughness and abrasion resistance in comparison with the afore-mentioned.

*Tungsten carbide*,<sup>20</sup> either in the form of small cast slugs or as sintered shapes made by powder metallurgy, can be readily wetted by many iron and nonferrous alloys. Cutters for machine tools, such as lathe tool bits, are widely available as steel shanks containing a cutting edge of cemented carbide brazed into place. This is a common example of the carbide insert method of providing maximum wear resistance at low cost. The principle can be adapted to any surface or edge that does not encounter heavy impact or stress concentration. A very important and widespread application is the hard setting of the cutting or wearing parts of oil-well-drilling tools.

Maximum hardness at elevated and atmospheric temperatures, high modulus of elasticity, and very high abrasion resistance must be balanced against high cost and minimum impact resistance. The carbide

inserts will crack readily from either blows or the thermal stresses of localized heating. High initial cost, which is tending to decrease as manufacturing techniques improve, may be unimportant, however, when service records are compared with lower-cost substitutes.

TABLE 14-10. CLASSIFICATION OF MATERIALS EMPLOYED FOR HARD-SURFACING METALS

A. *Intermetallic Compounds.* These are very hard and are employed as inserts for "hard setting" or appear as microscopic constituents in weld deposits.

I. *Carbides of:*

- |                 |                                      |
|-----------------|--------------------------------------|
| (a) Boron.      | (f) Tantalum.                        |
| (b) Tungsten.   | (g) Chromium.                        |
| (c) Molybdenum. | (h) Silicon.                         |
| (d) Titanium.   | (i) Iron, and combinations of these. |
| (e) Columbium.  |                                      |

II. *Nitrides of:*

- |               |           |
|---------------|-----------|
| (a) Chromium. | (c) Iron. |
| (b) Aluminum. |           |

These are seldom featured in hard surfacing, though they may be present in weld deposits. They do provide outstanding performance as surface layers on nitrided metals. They are included here for completeness though they are usually developed by a gaseous treatment rather than by weld deposition.

III. *Borides of:*

- (a) Chromium.

Boron carbide, which is perhaps the hardest substance known next to diamond, has not been exploited as a hard-surfacing constituent, though it is possibly present as a microconstituent in weld deposits containing both boron and carbon. In contrast to the other carbides, which are heavy and metallic, boron carbide is quite light (sp. gr.  $2.5 \pm$ ).

B. *Composite Metals* containing hard compounds of group A in matrix materials from group C. The heterogeneity of these is usually on a gross or macro scale in comparison with the mixed structural constituents of group C.

C. *Alloys* that are homogeneous during the molten stage of deposition.

I. *Cobalt-Base Alloys:*

- (a) Chromium-cobalt-tungsten (Stellite type).
- (b) Chromium-cobalt-tungsten with high carbon.
- (c) Chromium-cobalt-tungsten-nickel.
- (d) Chromium-cobalt-molybdenum (Vitalium type).
- (e) Chromium-cobalt-molybdenum-nickel.
- (f) Chromium-cobalt-iron with tungsten, molybdenum, nickel, etc.

II. *Nickel-Base Alloys:*

- |                                 |                                 |
|---------------------------------|---------------------------------|
| (a) Nickel-chromium-boron.      | (d) Nickel-iron-molybdenum.     |
| (b) Nickel-iron-chromium-boron. | (e) Nickel-silicon.             |
| (c) Chromium-nickel-iron.       | (f) Nickel-copper (Monel type). |
1. Heat-resistant alloys.
  2. Corrosion-resistant alloys.

TABLE 14-10. CLASSIFICATION OF MATERIALS EMPLOYED FOR HARD-SURFACING METALS (*Continued*)III. *Iron-Base Alloys:*

Classification based on structure where possible.

- (a) Irons (ferrites). These are soft and usually unsuitable for hard facing. With chromium they may serve for stainless or heat-resistant applications.
- (b) Steel (carbon less than 1.7%; hardness is influenced by heat treatment:
  - 1. Ferritic steels (usually soft like the irons above).
  - 2. Pearlitic steels. These exhibit their particular structure best at 0.80% and 0.90% carbon. These are economical and do not require alloying to produce this structure.
  - 3. Martensitic steels. These make possible high hardness levels but require carefully balanced alloy additions.
  - 4. Austenitic steels (usually containing high manganese, which makes possible extreme toughness). These require considerable alloy content.
- (c) Cast irons (carbon above 1.7%):
  - 1. Gray cast irons (soft and usually unsuitable for hard facing).
  - 2. Mottled cast irons (usually unsuitable).
  - 3. White cast irons. In this group falls some of the most useful and economical hard-facing alloys:
    - (1) Ferrite matrix (unusual).
    - (2) Pearlitic matrix. Brinell hardness around 400. Abrasion resistance to quartz sand relatively poor, though with softer abrasives performance may be acceptable. Inexpensive. Properties similar to surface of chilled iron castings.
    - (3) Martensitic matrix. Brinell hardness up to 700. Excellent abrasion resistance. Properties considerably dependent on manufacturing control and weld deposition conditions.
    - (4) Austenitic matrix. Brinell hardness up to 600. Relatively tough for cast irons. Good general wear resistance but sometimes disappointing abrasion resistance. Matrix alloys may confer special properties such as heat or corrosion resistance.

If a surface is armored with carbide inserts, subsequent wear may cause them to stand in relief. If a smooth surface is required, this may become a distinct disadvantage, and a homogeneous deposit may, therefore, be preferable. A very thin deposit is not usually practicable. See Fig. 14-10 and Fig. 14-11.

Oxyacetylene welding is generally recommended for the hard setting discussed previously.<sup>1</sup>

In general, the procedure involves, first, cutting grooves in the steel base metal by means of either an oxyacetylene cutting blowpipe or a forging hammer. The size and spacing of the inserts will vary with the type tool. The steel in one groove should be melted with an excess acetylene flame. One insert should then be picked up with the heated end of a high-strength steel welding rod and partially submerged in

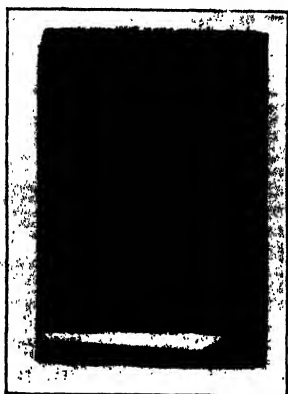


FIG. 14-10. Mosaic of Six Cemented Tungsten Carbide Inserts Brazed to a Block of SAE 1020 Steel. The abraded face shown was the result of two standard wet-quartz-sand abrasion tests. The abrasion factors obtained were 0.16 and 0.18 in comparison with the standard of 1.00 for annealed SAE 1020 steel.

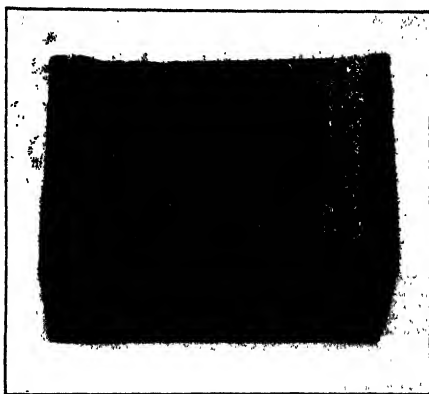


FIG. 14-11. Mosaic of Angular Tungsten Carbide Fragments Set in a Matrix of Martensitic Cast Iron (Ni-Hard). Note the differential wear. Mechanical loss of the harder fragments may occur when the matrix is deeply worn by loose abrasive. The wet-sand abrasion factor of this face was 0.36 versus 1.00 for annealed SAE 1020 steel.

the molten puddle. Finally, the insert should be completely covered over with the steel welding rod. This operation is repeated until the desired number of inserts have been set. Maximum wear resistance is said to result when a final coating of hard-facing alloys of the following group is deposited over the inserts.

*Composite tungsten carbide welding rods* are a more convenient arrangement for exploiting the wear resistance of this material. They cost less, but the deposits usually have lower abrasion resistance. Various devices are used to secure the simultaneous deposition of carbide particles and of the matrix alloy, one of the most common being a thin



steel tube containing granules of tungsten carbide. The tubes can be coated for electric-arc deposition like other rods.

Undissolved particles impart a sluggishness to the molten material that prevents ready flow or placement of the deposit. If the contained carbides are coarse, they sink to the bottom; if very fine, they may dissolve in and alloy with the matrix metal. In the latter case, the properties of tungsten carbide are replaced by those of a modified

matrix alloy, and smoother thinner deposits with somewhat higher impact resistance are obtainable.



60×

FIG. 14-12. Composite Structure of Hard-Surfacing Welding-Rod Alloy. The constituents are angular spines of chromium carbide with a six-sided cross section dispersed in a eutectiferous matrix of carbides and austenite. Hardness: Rc 47.

C%	Mn%	Si%	Cr%
3.05	7.38	0.33	34.15

presence of the refractory tungsten carbide particles which are not melted during the application. It is best to avoid keeping the deposit molten for too long a period. The welding tip should be large enough to produce a flame which will supply the required amount of heat with the pressure low enough to avoid blowing the molten metal.

The composite nature of the wear-resistant surface is obvious in the two materials already mentioned. It is less apparent in many other hard-surfacing alloys because the heterogeneity is on a microscopic scale. Nevertheless, the alloy cast irons, the high-carbon chromium-cobalt-tungsten grades, and some other types are structurally similar; that is, they consist of very hard carbide particles supported in a softer tougher matrix (compare Figs. 14-11 and 14-12). Figure 14-10 illustrates a surface armored with a mosaic of cemented tungsten carbide inserts set in a matrix of brazing alloy. The abrasion factors obtained

These materials consist essentially of two types—composite and tube—both of which are applied in much the same manner. The operation should be performed with the oxyacetylene process, using a flame containing a small excess of acetylene. The application should be made without penetrating as deeply into the base metal as in ordinary steel welding. A certain amount of stirring with the rod is necessary to obtain the most even distribution of the deposited metal. These rods do not flow so freely as most ordinary welding rods, owing to the

for this face were 0.18 and 0.16 (duplicate tests). It is significant that appreciable wear has occurred even though tungsten carbide is harder than the quartz abrasive employed.

#### COBALT-BASE ALLOYS—CHROMIUM-COBALT-TUNGSTEN TYPES

A group, sometimes referred to as nonferrous hard-surfacing alloys, is composed chiefly of cobalt, chromium, and tungsten in various pro-

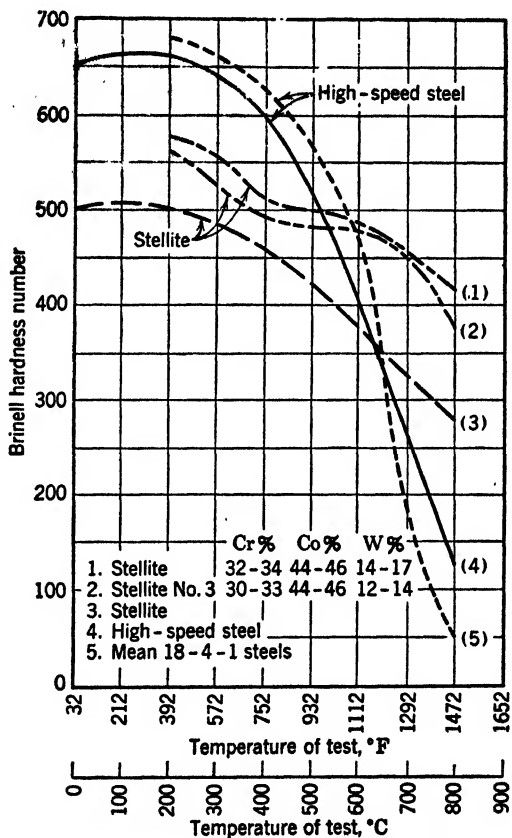


FIG. 14-13. Comparison of Hot Hardness—Stellites versus High-Speed Steel.  
References: 1, 2, 5 AIME, V. 105, p. 114, Harder & Grové (1933). 3, 4 ASST,  
V. 11, p. 725, Lantsberry (1927).

portions, with carbon as a very important minor element. Other elements, such as molybdenum or columbium, may replace or accompany the chief components. These have been widely exploited under the

trade name of "Stellite," which is the forerunner of the variety of currently available materials of this type.

Nominal compositions may range up to 35 per cent chromium and 20 per cent tungsten, with the remainder chiefly cobalt. Largely because of their chromium content, they are stainless and nontarnishing. The component metals have high melting points and have conferred a similar resistance to heat on the alloys. Their heat resistance includes two vital factors: oxidation or hot-gas corrosion resistance and elevated temperature strength, which is best represented in the hard-surfacing field by hot hardness.

TABLE 14-11. HOT-GAS CORROSION RESISTANCE OF CHROMIUM-COBALT-TUNGSTEN ALLOYS

Data Interpolated and Converted to English Units

Alloy No.	Chemical Analysis						Penetration, in./year *			
	C%	Mn%	Si%	W%	Cr%	Co%	Remainder	1600°F	1800°F	2000°F
1	1.16	0.39	1.17	7.6	26.8	$\frac{56.5}{60.9}$	Fe	0.050	0.075	0.275
2	1.87	0.49	2.08	3.5	26.1	$\frac{33.3}{36.2}$	Fe	0.070	0.265	0.707
3	1.43	0.60	2.41	3.65	26.0	$\frac{33.6}{34.0}$	Fe	0.080	0.110	0.445
4	$\frac{0.94}{1.00}$	10.18	2.11	4.90	$\frac{21.9}{22.7}$	32.6	Fe	0.040	0.080	0.215
5	1.68	0.56	1.76	5.40	27.8	$\frac{29.8}{30.4}$	Fe	0.050	0.125	0.345
6	2.2	0.45	0.85	....	28.9	....	Fe	0.080	0.580	1.165

Cobalt-containing hard-facing alloys, tested for scaling resistance at 1650°F to 2010°F in combustion products of doped gas (1.8% ethyl). Specimen exposed directly to burning fuel mix for ten 5-hr periods.

\* Based on: H. Cornelius, *Stahl u. Eisen*, 64 (1944), 529-532.

In the selection of these alloys for hard surfacing, hardness above 1000°F should receive primary consideration (Fig. 14-13). Various sources give temperatures ranging from 795° to 1250°F as the point at which Stellite begins to exceed the hardness of high-speed steel.<sup>21, 22</sup> Although the available data refer to tool steels, there is enough probability of a similar relationship between high-speed steels and highly alloyed iron-base alloys employed for welding to provide a basis for selection. Of course, if specific properties on proposed welding rods are presented to the engineer, the problem is simplified; unfortunately, such data are scarce in the hard-surfacing field.

Scaling and corrosion resistance are secondary properties that may be important but are less often required.<sup>23</sup> Hot-gas attack of the 30 per cent chromium alloys is not serious below 1800°F, whereas resistance is good in the less severe media, in air, in foods, and in some strong acids, such as nitric, acetic, citric, formic, lactic, sulfuric, sulfurous, and trichloroacetic. As a comprehensive discussion of corrosion is out of place here, it must suffice to suggest caution in applying these alloys under severe conditions. A preliminary field test, including all service factors, is advisable, as sometimes minor variables may be decisive.

TABLE 14-12. ROOM-TEMPERATURE TENSILE PROPERTIES, CHROMIUM-COBALT ALLOYS

Chemical Analysis				Yield	Ult. Tens.	Elong.	Red.	Hardness,
C%	Cr%	Co%	Others	Strength, psi	Strength, psi	in 2", %	Area, %	BHN
0.30	27.4		Fe% = 68.4 ±		67,250	0.5	nil	238
0.35	26.2		Ni% = 70.6	44,000	73,250	15	15	179
0.31	26.6	69.0		63,000	82,500	6	7	269
0.50	26.9	69.3		69,000	87,500	4	4	297
0.73	26.5	69.3		71,000	90,500	2	2	321
0.55	26.3	62.6	Mo% = 6.9	81,000	96,250	4	4	364
0.53	26.3	62.8	W% = 6.9		106,500	1	1	321
0.50	26.4	62.8	Cb% = 7.0	68,000	100,250	nil	nil	364

These alloys are particularly valuable for hard-facing parts subjected simultaneously to wear, high temperature, and corrosion, as in valve seats. Similar alloys containing nickel in addition to chromium, cobalt, and tungsten are also being applied as valve facings (Table 14-11).

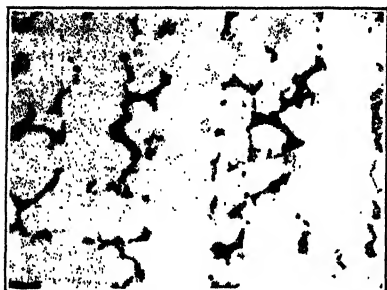
Tarnish resistance up to 500°F coupled with a reflectivity of 68 to 85 per cent (versus 91 to 98 per cent for a new silver mirror of highest quality or 68 to 95 per cent for a lacquered silver mirror) have led to the use of Stellite for mirrors in scientific instruments.<sup>24</sup>

Although strength at elevated temperatures is high, at room temperature the combination of strength and ductility is not especially favorable. The values in Table 14-12 are suggestive as probable maxima. They were determined on sound cast test specimens; the variables introduced by welding generally tend to produce lower results. It may be noted that carbon decreases ductility and increases strength, this being a variable that may come either from the initial welding-rod composition or from carbon absorption in the oxyacetylene flame.

In Table 14-12, a comparison of the effects of cobalt-, nickel-, and iron-base alloys is possible. The hardness ranking applies also to elevated temperature strength, with the exception of the iron-base alloy,

which is much weaker than the others. (This correlation is fortuitous here and is not generally applicable.)

Abrasion resistance, especially if the abrasion is wet and high temperatures do not develop, should not be considered a marked characteristic of the lower-carbon chromium-cobalt-tungsten alloys. This state-



150X

Fig. 14-14. Low-Carbon Chromium-Cobalt-Tungsten Alloy (Stellite Type).

C%	Mn%	Si%	Ni%
0.53	0.68	1.25	0.34
Cr%	Co%	W%	Fe%
26.3	62.8	6.93	0.84

A few eutectic carbides are scattered in a dendritic pattern throughout the solid-solution matrix. This material has excellent corrosion and heat resistance and outstanding retention of hardness and strength at elevated temperatures. Its hardness at atmospheric temperature is low for a facing alloy (BHN = 321) and it has very poor wet-sand abrasion resistance.



150X

Fig. 14-15. Low-Carbon Chromium-Cobalt-Molybdenum Alloy (Vitalium Type).

C%	Mn%	Si%	Ni%
0.55	0.66	1.33	0.31
Cr%	Co%	Mo%	Fe%
26.3	62.6	6.90	0.88

Note the similarity in structure to the Cr-Co-W alloy in Fig. 14-14. This material has properties much like those of Stellite. It derives its name from its use as "human hardware." Employment as a hard facing is not recommended unless heat resistance and high-temperature strength are required.

ment is somewhat at variance with popular ideas and requires explanation, which is provided by an examination of structures and abrasion test data. If carbon is relatively low, the structure, as revealed by microscopic examination, consists of a solid-solution matrix containing some scattered carbides in eutectiform arrangement (Figs. 14-14 and 14-15).

An increase of carbon from 0.53 to 1.04 per cent causes an increase in hardness to 444-460 BHN, which is explained by the increased

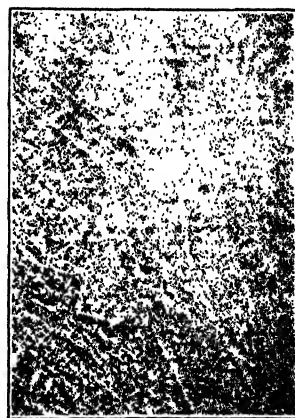
number of small carbide particles (Fig. 14-16) arranged in a dendritic pattern (Fig. 14-17).

The associated wet-sand abrasion factor is so high, however, that the expense in comparison with ordinary steels is not justified. A further increase to 2.65 per cent carbon causes distinctive rods or pseudo-hexagonal crystals (Figs. 14-18 and 14-19) to appear in the micro-



300X

Fig. 14-16.



300X

Fig. 14-17.

C%	Mn%	Si%	Cr%	Co%	W%	Fe%
1.04	3.52	1.59	27.6	60.0	3.52	1.86
Hardness			Wet-Sand Abrasion			
Rc		BHN	Factors			
48		460	1.03 and 1.23			

**Arc-Weld Deposit.** This grade is employed for some hard-facing applications but is too low in carbon for good abrasion resistance.

structure. These are believed to be complex chromium carbides, whose presence is associated with a marked improvement in abrasion resistance. These carbides resulted from crystallization from a molten-weld deposit, but otherwise the analogy with the composite tungsten carbide type is obvious. Note their similarity to those in Fig. 14-12. Their relative scratch hardness in comparison with the matrix may be seen in Fig. 14-20.

Thus, the high-carbon chromium-cobalt-tungsten alloys may have good abrasion resistance as well as hot hardness. However, if elevated temperatures are not involved, the expensive cobalt-base alloys do not

appear economically justified; equal or better abrasion resistance may be obtained from martensitic cast-iron welding-rod deposits as described later.

Wet-sand abrasion test results appear in Table 14-13.

#### NICKEL-BASE ALLOYS

Nickel hard-surfacing alloys are not common. There is available one group, however, that features hardening by chromium boride. Test



60X

FIG. 14-18.

C%	Mn%	Si%
2.64	1.52	0.89



300X

FIG. 14-19.

C%	Mn%	Si%	Cr%	Co%	W%	Fe%
2.64	1.52	0.89	30.7	45.5	14.0	3.6

Oxyacetylene Weld Deposit.

Hardness	
Rc	BHN
55	512

Wet-Sand Abrasion	
Factors	
0.71 and 0.73	

Six-sided spines of chromium carbide appear in a eutectiferous matrix. Note the similarity in structure to Fig. 14-12. The average microhardness is 1900 VPN and 1900 I Knoop for the carbides; with 347 VPN and 410 I Knoop for the matrix.

data for several of these appear in Table 14-14, which includes an iron-molybdenum base with similar hardening elements for comparison.

The 65 to 75 per cent nickel, 13 to 20 per cent chromium alloy with 2.75 to 4.0 per cent boron is said to have high red hardness, very high wear resistance, and very high corrosion resistance. The wear resistance probably is best developed in metal-to-metal contact where heat and corrosion are involved. Its wet-sand abrasion resistance is not high enough to justify its recommendation for related service. The

alloys as a group are probably most comparable to the chromium-cobalt-tungsten type that are hardened with carbon. In both, red hardness and corrosion resistance are factors that should determine



300X

Fig. 14-20. Electric-Arc Weld Deposit.

C%	Mn%	Si%	Cr%
2.62	3.62	1.02	31.8

Co%	W%	Fe%
43.1	14.1	4.1

Hardness		Wet-Sand Abrasion Factors
Rc	BHN	
60	600	0.45 to 0.50

The spines, seen as six-sided crystals when cut transversely, are chromium carbides that probably are complex in composition. The matrix consists largely of a eutectic (or low-melting) mixture of solid solution and carbide, with some elliptical islands of solid solution similar to the matrix of Fig. 14-14. Microcharacter hardness is about 6500 for the carbides and 2200 for the matrix. Note how the diamond scratch changes width as it crosses the constituents. On Mohs's scale the carbides are about 9+ and the matrix about 6½.



150X

Fig. 14-21. Electric-Arc Weld Deposit.

C%	Ni%	Cr%	B%
0.95	70.0	16.2	2.85

Hardness		Wet-Sand Abrasion Factor
Rc		
62		0.95

Note the very hard particles standing in relief. They are reported to be chromium boride. Their Knoop hardness is about 2900; VPN = 2670. Despite their high hardness they are not effective in conferring abrasion resistance, probably because of their brittleness. The six-sided crystals in the background suggest chromium carbides.

their selection. With high hardness, they may have excellent resistance to galling, but this property may be obtained more economically with martensitic cast irons or steels.

Without the boron and with about 0.50 per cent carbon, the nickel-chromium alloy represents a standard heat-resistant grade that is fre-



quently specified for castings, particularly for carburizing containers and cyclicly heated furnace parts. It is a member of a group of alloys that have outstanding hot-gas corrosion resistance and excel-

TABLE 14-13. ABRASION RESISTANCE OF CHROMIUM-COBALT-TUNGSTEN WELD DEPOSITS

Type	Composition				Rc	BHN	Wet-Sand Abrasion Factors	Weld Method
	C%	Cr%	Co%	W%				
1		$\frac{28}{32}$	$\frac{48}{52}$	$\frac{10}{15}$ *	45		0.98; 1.01	
6		$\frac{27}{30}$	$\frac{63}{68}$	$\frac{2}{6}$ *	40		1.36	
12		$\frac{30}{34}$	$\frac{52}{58}$	$\frac{6}{10}$ *	49		1.22	
1	2.6	31	46	14 †	55	512	0.72; 0.71	Oxyacetylene
	2.6	31	46	14	56	512	0.54; 0.49	Oxyacetylene
1	2.6	32	43	14 †	59	600	0.45; 0.50; 0.59	Electric arc
	2.6	32	43	14	60	600	0.61; 0.62	Electric arc
6	1.0	28	60	3.5 †	48	460	1.03; 1.20; 1.23	Oxyacetylene
	1.0	28	60	3.5	47	444	1.21; 1.22	Oxyacetylene

\* Nominal composition of type alloy.

† Welding-rod composition.

TABLE 14-14. ABRASION RESISTANCE OF NICKEL-CHROMIUM BORIDE WELD DEPOSITS

Type	Composition						Wet-Sand Abrasion			Weld
	C%	Ni%	Cr%	B%	Mo%	Fe%	Rc	BHN	Factor	Method
	0.95	69	16	2.9			46	444	1.11	Electric arc
4 *							58	444	1.00	Electric arc
							62	652	9.95	Electric arc
		$\frac{75}{85}$	$\frac{8}{14}$	$\frac{2}{3}$			31	302	1.16	Oxyacetylene
6 *		$\frac{65}{75}$	$\frac{13}{20}$	$\frac{2.75}{4.75}$			56	555	1.17	Electric arc
							61	627	0.85	Oxyacetylene
9 *			$\frac{7}{11}$	$\frac{1}{2}$	$\frac{12}{16}$	remainder	63	600	0.73	Electric arc
							58	627	0.44	Oxyacetylene

\* Nominal compositions.

lent strength at elevated temperatures. The higher nickel compositions also have good resistance to carburization and resist embrittlement (at red heats) from carbon absorption. They are available as castings or welding rods.

These nickel-chromium-iron alloys are not intended for hard surfacing, but, where heat resistance and corrosion resistance to hot gases or cold liquids are required, they may provide very satisfactory overlays. For convenience, several of the most important are listed in Table 14-15, with test data indicative of their oxidation resistance and mechanical properties. These alloys (except the HC Type) are characterized by an austenitic matrix containing scattered chromium carbides. Some of them are nonmagnetic and are useful because of this property.

A series of nickel-base alloys intended primarily for corrosion resistance and normally furnished as castings may be weld-deposited<sup>25-27</sup> to provide overlays with exceptional stability to certain media. Nominal compositions appear in Table 14-16, and general properties in Table 14-17. Grades A and E are also available in wrought form.

The 60 per cent nickel, 20 per cent molybdenum, 20 per cent iron alloy is employed primarily for resistance to hydrochloric acid, which rapidly attacks practically all the stainless steels in concentrations about 1 to 3 per cent, and may be destructive when even weaker, if at elevated temperatures. The molybdenum content apparently confers marked resistance to such corrosion. The alloy also performs well in sulfuric, formic, and acetic acids; salt-spray environments; and alkalis. It is vulnerable to nitric acid and to free chlorine. The higher-molybdenum grade is appropriate for handling boiling hydrochloric acid and wet HCl gas.

The modification with about 15 per cent chromium has similar properties,<sup>28</sup> but is slightly better in sulfuric acid and is also suitable for oxidizing media such as nitric acid, free chlorine, and acid cupric or ferric salt solutions.

The 10 per cent silicon grade has fair resistance to cold hydrochloric acid; is excellent in acetic, formic, and phosphoric acids; and is well suited for handling sulfuric acid or sulfur trioxide.

The nickel-copper alloy,<sup>26</sup> which is very widely used in wrought form, is valuable for corrosion resistance in many applications. Sulfuric acid up to 80 per cent; hydrochloric acid up to 5 per cent (if quiet and not heated; cold phosphoric acid; acetic, formic, tartaric, lactic, citric, oxalic, and malic acids; sodium chloride solutions; alkalies; fresh and sea water; food products; and steam are usually resisted satisfactorily. Agitation, aeration, and high temperatures tend to increase the severity of corrosion. Nitric and sulfurous acids, ferric salts, stannous and mercuric salts in acid solution, alkaline hypochlorite solutions, fused sulfur and low-melting metals should not be used with this alloy.

TABLE 14-15. PROPERTIES OF IMPORTANT HEAT-RESISTANT ALLOYS \*

Type	28Cr	21Cr-9Ni	26Cr-12Ni	26Cr-20Ni	16Cr-35Ni	12Cr-60Ni
ACI Designation	HC	HF	HH	HK	HT	HW
C% †	0.30	0.25-0.35	0.30-0.40	0.27-0.71	0.35-0.70	0.31-0.77
Ni%	0-3	8-11	10-13	19-21	34-37	59-62
Cr%	27-30	18-23	23-27	23-26	13-17	10-14

	<i>Room Temperature Tensile Properties ‡ On Small Castings</i>					
Yield strength, psi	40,000-50,000	40,000-54,000	62,000-83,000	40,000-53,000	36,000-39,000	
Ultimate str., psi	73,000-95,000	80,000-95,000	66,000-100,000	65,000-71,000	68,000-78,000	
Elongation, %	0.5	27-47	14-40	6-26	5-14	3-13
Red. area, %	0.5	26-40	13-45	7-25	5-18	4-11
Hardness, BHIN	238	163-181	160-190	175-202	150-195	160-220

	<i>Hot-Gas Corrosion as Metal Loss in in. Per Year §</i>					
In air at 1600°F	0.019	0.013	0.007		0.0063	0.0055
	0.017	0.001	0.005	0.004	0.004	0.0043
In air at 1800°F	0.048	0.14	0.039	0.025	0.029	0.012
	0.038	0.037	0.030	0.02	0.0097	0.0092
In air at 2000°F	0.063	0.6	0.097	0.17	0.26	0.045
	0.05	0.1	0.071	0.049	0.048	0.037

	<i>In Oxidizing Glue Gas</i>		
5 gS per 100 cu ft, 1800°F	0.029	0.14	0.036
		0.035	0.029
			0.029
			0.026
			0.075
			0.025
			0.038
			0.024

100 gS per 100 cu ft, 1800°F	0.033	0.12	0.033	0.027	0.085	0.05
5 gS per 100 cu ft, 2000°F	0.03	0.033	0.027	0.024	0.024	0.028
	0.50	1.0	0.5	0.15	0.30	0.07
	0.15	1.0	0.10	0.05	0.07	0.025
100 gS per 100 cu ft, 2000°F	0.17	1.0	0.12	0.07	0.25	0.07
	0.07	0.10	0.07	0.03	0.04	0.02
<i>In Reducing Flue Gas</i>						
5 gS per 100 cu ft, 1800°F	0.026	0.34	0.048	0.028	0.056	0.027
	0.025	0.046	0.026	0.022	0.026	0.017
100 gS per 100 cu ft, 1800°F	0.034	0.48	0.036	0.025	0.46	1.8
		0.034	0.028	0.022	0.036	0.036
5 gS per 100 cu ft, 2000°F	0.25	1.0	0.3	0.10	0.15	0.03
	0.04	0.3	0.035	0.02	0.04	0.02
100 gS per 100 cu ft, 2000°F	0.5	1.0	0.5	0.10	1.0	1.0
	0.07	0.4	0.05	0.025	0.10	0.025

\* In the design of HRA parts, creep and rupture strength are vital properties; in weld overlays they may usually be neglected as the load-carrying properties of the base metal overshadow them.

† Nominal range to cover tensile properties given here; not part of usual specifications.

‡ Data from research program of The Electro Alloys Division, Elyria, Ohio.

§ Data from research program sponsored by the Alloy Casting Institute at Battelle Institute; test specimens provided by the Experimental Foundry of the American Brake Shoe Company. The significant elements other than Cr and Ni were: C: 0.31-0.50%; Mn: 0.67-0.90%; Si: 0.76-1.35%; and N: 0.01-0.14%. The ranges given reflect the Cr and Ni extremes.

As these metals are relatively expensive, especially with high molybdenum contents, stainless steel should receive first consideration for suitability. For general corrosion resistance, and especially for nitric acid service, the austenitic chromium-nickel-iron alloys, typified by 18 per cent chromium, 8 per cent nickel, are satisfactory and less costly.

TABLE 14-16. NOMINAL COMPOSITIONS OF NICKEL-BASE CORROSION-RESISTANT ALLOYS

Type	Chemical Analysis						
	Ni%	Cr%	Mo%	Fe%	Si%	Cu%	Al%
A	60		20	20			
B	65		30	5			
C	60	15	17	8			
D	85				10	3	2
E	69			2	1	28	

TABLE 14-17. PHYSICAL AND MECHANICAL PROPERTIES OF SEVERAL NICKEL-BASE CORROSION-RESISTANT ALLOYS

Type	Cast Metal				
	A *	B *	C *	D *	E †
Yield strength, 1000 psi	42-45	55-57	45-48		30-60
Ult. tens. str., 1000 psi	69-78	75-82	72-80	36-41	65-100
Elongation, % in 2 in.	8-12	6-9	10-15	0	5-35
Red. of Area, %	16-18	10-13	11-16	0	5-35
Hardness, BHN	155-200	190-230	175-215	(Rc 50-55)	125-150
Specific gravity	8.80	9.24	8.94	7.80	8.80
Thermal conductivity (BTU/ft <sup>2</sup> /in./hr/°F)	116	79	87	145	174
Electrical resistivity Microhn per cm <sup>3</sup>	127	135	133	113	43
Magnetic permeability	5	4	4		
Specific heat, cal/°C	0.0939	0.0907	0.0930	0.1086	0.127
Thermal expansion Micro in./in./°F (32-212°F)	6.1	5.6	6.3	6.1	7.8

\* *Hastelloy High-Strength, Nickel-Base, Corrosion Resistant Alloys*, a pamphlet published by Haynes Stellite Co., Kokomo, Ind., 1940. (Welding details appear on pages 28-30.)

† *Engineering Properties of Monel Metal*, Bull. T-5, Intern. Nickel Co.

## IRON-BASE ALLOYS

The distinctions among soft iron, steel, and cast iron are based on carbon content. As the low-carbon ferrites, typified by ingot iron and wrought iron, have little value for hard surfacing, the important ferrous

materials should be considered as alloys of iron and carbon, sometimes modified by additions of hardening and strengthening elements. The division between steels and cast irons is usually drawn at 1.7 per cent carbon, which is the maximum that unalloyed iron can hold in solid solution. This percentage is changed by alloying elements. The amount of carbon has an important influence on hardness, which is increased, and toughness, which may be decreased, as carbon is raised.

#### STEELS FOR HARD SURFACING

Steels are recommended for hard surfacing where strength and toughness are important and economy is a consideration. The chromium-cobalt-tungsten types previously described are also tough and strong if carbon is low, but the cobalt base is usually a needless expense. The unique position of steel as an engineering material is paralleled in the welding-rod field. As with structural and special-purpose steels, a classification based on structure is most significant.

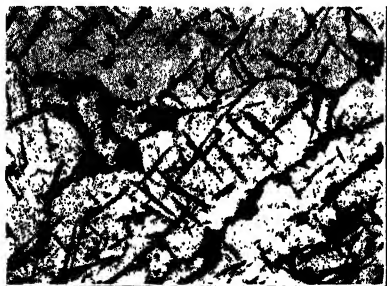
The common constituents of steel are (a) austenite, which is tough and strong; (b) ferrite, which is soft and ductile and is essentially low-carbon iron; (c) cementite, or iron carbide ( $\text{Fe}_3\text{C}$ ), which is hard and brittle; and several aggregate constituents that are composed of mixtures of ferrite and cementite. The most common is (d) pearlite, which consists of alternate plates of ferrite and cementite arranged as lamellas. A slowly cooled steel containing about 0.85 per cent carbon will consist almost entirely of pearlite; rail steel or SAE 1085 are typical examples. Pearlite is moderately strong and hard but not particularly ductile.

Low-alloy steels with carbon contents between 0.05 per cent and 0.85 per cent will exhibit various proportions of ferrite and pearlite, with properties intermediate between the extremes depending on carbon content. The low-carbon grades have little merit for hard surfacing, although for other welding work they may have wide applicability.

The other aggregates are usually the result of either alloy additions, heat treatment, or both. They are (e) bainite, which has several modifications; (f) martensite, which is very hard and strong; and (g) spheroidite, which is relatively ductile.<sup>29</sup> The carbon that in a slowly cooled steel will appear as alternate lamellas in pearlite will develop an acicular martensitic pattern if the same steel is drastically cooled, as by quenching, from above the critical temperature. (The critical temperature, which varies for different steels but is usually between 1300° and 1400°F, is the point at which iron undergoes a marked change in its power to dissolve carbon because of an atomic rearrangement in the

crystals. The solid solution of carbon in iron above this temperature is austenite.)

Bainite is difficult to produce by continuous cooling and thus seldom appears in weld deposits, though with certain compositions it may occur, usually mixed with pearlite. Bainite alone has an excellent combination of strength and ductility, but the mixed structures are generally inferior. Martensite forms only on continuous cooling, which must be rapid enough to avoid previous formation of pearlite or bainite.



60×

FIG. 14-22. Brittle Structure of Hadfield's Manganese Steel as Cast. The alloy in this condition is almost as brittle as cast iron.

If either bainite or martensite are reheated or "tempered," the tiny carbide particles they contain will agglomerate and form larger granular or spheroidal masses. This aggregate of rounded cementite particles in a matrix of ferrite is spheroidite. It is a desirable structure for machinability but not for wear resistance (Table 14-18).

itic, pearlitic, or martensitic as deposited and air-cooled. Subsequent heat treatment, if properly used, will develop the other structures also. (Ferritic steels are characteristically soft and, consequently, are omitted from this discussion.)

The chief function of alloys in steel is the control of structure, and they usually serve this purpose in welding-rod deposits also. Hard-surfacing overlays may be austenitic, pearlitic, or martensitic as deposited and air-cooled. Subsequent heat treatment, if properly used, will develop the other structures also. (Ferritic steels are characteristically soft and, consequently, are omitted from this discussion.)

### AUSTENITIC STEELS

The most widely known material of this type is Hadfield's austenitic manganese steel. It usually contains 1.0 to 1.4 per cent carbon and 10.0 to 14.0 per cent manganese when produced in cast form.<sup>30</sup> The function of the manganese is to inhibit the normal transformation of austenite to the constituents previously described. If rapid cooling from above the critical temperature occurs, no transformation takes place because of the sluggishness imparted by manganese, and the austenitic structure is retained indefinitely at atmospheric temperatures. Normal cooling after casting is too slow, however, and the as-cast alloy exhibits small amounts of cementite, pearlite, or martensite. These appear chiefly along crystal-grain boundaries, forming a brittle network, and confer very inferior properties. To austenitize

TABLE 14-18. APPROXIMATE MECHANICAL PROPERTIES OF VARIOUS UNTEMPERED STRUCTURES

Structure	Description	Y.S., psi	T.S., psi	% El., 2"	R.A.	BHN *	Rc Rb §	VPN *	Room Temp. Charpy V, ft-lb
Ferrite †	Single-phase alpha iron + low-carbon content	6,000 † 30,000 ‡	35,000 † 60,000 ‡	60 † 50 ‡	95 90	90 180	40 70	90 130	50
Spheroidite ‡	Ferrite matrix with large globular carbides	40,000 ¶	90,000 ¶	30 ¶	70 ¶	190 -	90 Rb ¶	190	80 **
Coarse pearlite ‡	Coarse lamellar structure of ferrite and carbide	50,000 ¶	110,000 ¶	12 ¶	20 ¶	280	20 ¶	240	10 **
Fine pearlite ‡	Fine lamellar structure of ferrite and carbide	130,000 ¶	180,000 ¶	14 ¶	35 ¶	375	40 ¶	390	10 **
High-temperature bainite ‡	Fine aggregate of ferrite and carbide particles	140,000 ¶	180,000 ¶	16 ¶	40 ¶	380	35 ¶	345	20 **
Low-temperature bainite ‡	Exceeding fine aggregate of ferrite and carbide particles	200,000 ¶	240,000 ¶	18 ¶	50 ¶	495	50 ¶	540	10 **
Martensite ‡	Single-phase structure with high amount of carbon in solution	320,000 **	350,000 **	2 **	5 **	700	65 **	920	5 **

\* BHN and VPN have been converted from Rc.

† Variation of properties from those obtainable in plain carbon ferrite to a practical maximum obtainable by alloying.

‡ Plain carbon (0.80% C) steels.

§ After Gensamer and Lacy, *The Tensile Properties of Alloyed Ferrites*, *Trans. ASM*, **32** (1944), 88-110.

¶ After Hoyt, *Métals & Alloys Data Book*.

\*\* W. S. Pellini, and Low. The Tensile Properties of Pearlite, Bainite, and Spheroidite, *Trans. ASM*, **30** (1942), 923-1021.

The tensile test ductility and notch-bend toughness of pearlites, bainites, and martensites, when tempered to a same low hardness, increase directly with increasing fineness of the structures.

Mixed structures are detrimental in varying degrees to mechanical properties; ductility values in particular may be markedly lowered by mixtures which differ widely in relative fineness.

For practical purposes, the mechanical properties of structures having similar distributions of ferrite and carbide are not affected by the addition of alloying elements.





60X

FIG. 14-23. Hadfield's Austenitic Manganese Steel after the Toughening Heat Treatment. The faint grain boundaries, which are frequently difficult to detect microscopically, are associated with toughness. If the austenitizing temperature is too low or if cooling from it is too slow, the boundaries are more prominent, and ductility is appreciably lowered. The abrasion factor of this structure ranges from 0.75 to 0.85.



60X

FIG. 14-24. Toughened Hadfield's Austenitic Manganese Steel after Work Hardening. The transformation or carbide precipitation evidenced by the numerous slip lines does not reduce ductility excessively as hardness is increased.



150X

FIG. 14-25.  
Reheated 2 hr at 1000°F

Heat No.	C%	Mn%	Si%
1.15	1.15	12.6	0.42



150X

FIG. 14-26.  
Reheated 48 hr at 800°F

Heat No.	C%	Mn%	Si%
45-235	1.18	13	0.50

Austenitic manganese steel that has been reheated after the toughening heat treatment. The transformation structures shown here are very inferior in toughness and should be carefully avoided.

and toughen the steel, it is reheated to about 1850°F and water-quenched, forming a uniform and very tough austenitic structure. This will not transform unless it is reheated to some temperature above about 600°F or is mechanically deformed. Reheating from 600° to 1400°F produces grain-boundary transformation that seriously embrittles the alloy. However, deformation, by cold work, usually from pounding or plastic flow in compression, causes a transformation that gradually exchanges ductility for hardness without developing any localized zones of weakness. As this commonly occurs at a working surface, the process becomes a kind of case hardening that is self-renewing as the metal is worn away. This combination of surface work hardening, high tensile strength (120,000 to 140,000 psi), high ductility (30 to 50 per cent elongation), toughness (Charpy impact above 90 ft-lb), and good wear resistance have led to wide use in applications involving abrasion and heavy impact.

Manganese steel welding rods may be required to build up worn areas of manganese steel castings, to repair fractures, or to provide a wearing surface on some dissimilar material. The latter use may be classed as hard surfacing, but with the qualification that some form of deformation is required to produce the hardening after the weld deposit is made.

It is not recommended that manganese steel deposits be applied to a weak or brittle base material. Toughness, not abrasion resistance, as such, is the unique property of austenitic manganese steel. It is better as a base than as a surface coating. Its chief usefulness is in building up the worn or battered-down portions of members that must be strong and tough, such as frogs and crossings in railway trackwork.

The nature of manganese steel introduces several metallurgical problems into welding practice. First, the base metal, if it is manganese steel, must be protected from overheating. As previously described, if

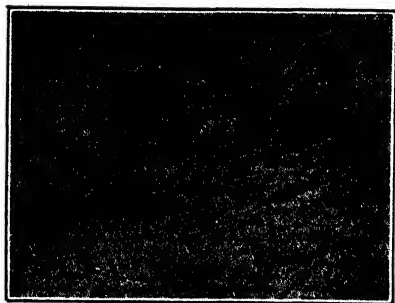


60×

FIG. 14-27. Arc-Weld Deposit from Austenitic-Nickel-Manganese Steel Rod. Note the relatively heavy grain boundaries that develop during air cooling of the base. As they are associated with lowered ductility, the toughness of weld areas seldom approaches that of properly toughened cast or wrought manganese steel. The low-carbon content and the sluggishness imparted by nickel have inhibited carbide precipitation in the weld metal, which appears above.

it exceeds 600°F for long, an embrittling transformation may occur. This is best avoided by electric welding, small-diameter rods, low welding currents, and careful procedure on the part of the welder.

The normal composition for casting is not satisfactory for welding, as field requirements generally prevent use of the toughening heat treatment. The structure should, therefore, be entirely austenitic after cooling from the welding heat. This is attained with a sacrifice of some toughness and strength by lowering carbon content and adding additional alloying elements, such as nickel and molybdenum, to make transformation even more sluggish. The alloys may be in the welding rod or incorporated in its coating, but inclusion in the metal rod is preferable as more homogeneous deposits result.



300×

FIG. 14-28. Electric-Arc-Weld Deposit of a Chromium-Molybdenum Steel Containing 1.5 per cent Carbon. This structure is representative of martensitic steel and is identified by the acicular pattern and relatively light etching behavior.

Hardness	Wet-Sand Abrasion
Rc	Factor
59	0.66

Austenite is characteristically nonmagnetic, and the deposits can usually be differentiated from other irons and steels by means of a hand magnet. Austenitic manganese steel, after toughening, usually has a magnetic permeability of 1.03 to 1.10,<sup>81</sup> which is too low for detection without sensitive instruments.

Most of the stainless steels are austenites produced by chromium and nickel rather than by manganese. They do not normally require quenching to retain their austenitic structure. They are available as welding rods and may be selected for overlays that require corrosion resistance primarily. A list of the common grades appears in Table 14-19. Unfortunately, a discussion of corrosion resistance would seriously complicate this chapter, and the reader is referred to other sources.<sup>32-36</sup>

Austenitic stainless-steel overlays intended for corrosion resistance in some liquids must be protected from a selective attack of the grain boundaries by intergranular corrosion, sometimes called weld decay. It may be avoided by "quench annealing" of the alloy from about 1950°F or by including carbide stabilizing elements, such as columbium or titanium, in the weld metal.

Grain-boundary corrosion is related to the precipitation of carbon from solid solution in the 900° to 1600°F range. It is frequently induced in stainless-steel stock by the heat of welding on it, trouble appearing in the weld zone sometimes after months of service. It may appear within weld metal, however, especially if carbon has been absorbed from the welding flame. Service heating around 1200°F coupled with or followed by liquid corrosion is a particularly bad combination. ASI types 321 \* and 347 are especially formulated to minimize intergranular corrosion.

TABLE 14-19. TYPICAL AUSTENITIC STAINLESS STEELS AND ALLOYS AVAILABLE AS WELDING RODS

Type†	Nominal Chemical Composition			
	3%	Cr%	Ni%	Others
301	0.15	16	7	.....
302	0.15	18	8	.....
302 B	0.15	18	8	2.5% Si
304	0.07	19	9	
307	0.10	19	9	0.5% Mo; 4% Mn
308	0.07	20	11	
309	0.10	23	13	
310	0.15	25	20	
311	0.10	17	25	
312	0.10	29	9	
316	0.08	18	13	2.0% Mo
317	0.08	19	14	3.0% Mo
330	0.15	15	35	
360*	0.15	13	60	
375*	0.15	14	75	
380*	0.15	20	79	
385*	0.15	15	84	
822*	0.03	15	55	15% Mo; 5% W
347	0.08	19	9	0.8% Cb
309 Cb	0.08	23	13	0.8% Cb
310 Cb	0.10	25	20	0.8% Cb
316 Cb	0.08	18	13	0.5% Cb; 2.0% Mo

\* Manufacturers designation.\*\*

† Note that not all of these correspond to American Iron and Steel Institute designations for wrought steels.

Most stainless overlay applications are served by columbium bearing type 347; type 308, which is the basic (19 per cent chromium, 9 per cent nickel) grade; by 316 and 317, which contain molybdenum for enhanced resistance to corrosion by sulfuric and sulfurous acids and

\* Not available as welding rod because welding characteristics are poor.

TABLE 14-20. MEDIA AT ROOM TEMPERATURE (70°F) IN WHICH 18-8 IS PRACTICALLY UNAFFECTED BY CORROSION

Acetic 10%, 33%, 100%	Alum	Potassium iodide
Acetic anhydride	Aluminum sulfate	Potassium nitrate
Benzoic	Ammonium bromide	Potassium oxalate
Boric	Ammonium carbonate	Potassium permanganate
Butyric	Ammonium alum, saturated, slightly acid with sulfuric acid, up to 200°F	Salt and sea water
Chlorosulfonic conc.		Silver bromide
Citric		
Hydrocyanic		Acetone
Lactic	Ammonium chloride	Benzol
Malic	Ammonium hydroxide	Camphor
Nitric, conc. plus 2% HCl	Ammonium nitrate	Coffee
Nitric	Ammonium sulfate plus 0.5% sulfuric acid	Copal varnish
Nitrous		Ethyl alcohol
Oleic	Barium hydrate	Ethyl ether
Phosphoric conc.	Barium carbonate	Food pastes
Phosphoric 10%	Calcium carbonate	Formaldehyde
Picric	Calcium chloride	Fruit juices
Pyrogallol	Calcium hypochlorite made slightly alkaline with NaOH	Gasoline
Stearic		Glue
Sulfuric conc.	Calcium hydroxide or oxide	Inks
Sulfurous	Copper carbonate	Lemon juice
Tannic	Copper nitrate	Lysol
Tartaric	Copper sulfate plus 2% H <sub>2</sub> SO <sub>4</sub>	Methyl alcohol
		Milk—fresh or sour
Silver nitrate	Ferric nitrate	Mustard
Sodium bisulfate	Ferrous sulfate	Naphtha
Sodium bromide	Glauber's salt	Oils—mineral or vegetable
Sodium citrate	Lead acetate	Paraffin
Sodium chlorate, 10% sol	Lactic acid salts	Paregoric compound
Sodium chlorate, 25% sol	Magnesium carbonate	Quinine sulfate
Sodium hydroxide	Magnesium chloride	Soaps
Sodium hypochlorite, slightly alkaline with NaOH	Magnesium sulfate	Sodium salicylate
	Mercurous nitrate	Soft soap
Sodium nitrate	Mercuric cyanide	Vinegar
Sodium peroxide at 212°F	Nickel nitrate	
Sodium sulfate	Nitrates	Atmosphere of steam, carbon dioxide, and air
Sodium sulfide	Nitrous acid salts	Atmosphere of steam, sulfur dioxide, carbon dioxide, and air
Sodium sulfite	Potassium bromide	Sulfur dioxide
Sodium thiosulfate plus 4% potassium bisulfate	Potassium chloride	Baking oven gases
Sodium thiosulfate 20% plus acetic acid 20%	Potassium cyanide	Calcium chloride
Soda ash 10% up to 200°F	Potassium dichromate	Mine water
Soda ash 50% up to 200°F	Potassium ferricyanide	Steam and air, refluxed
Spirits of niter	Same boiling	

salts, and to pitting; and by 309 (24 per cent chromium, 12 per cent nickel) or 310 (25 per cent chromium, 20 per cent nickel), which are low-carbon compositions similar to the HH and HK heat-resistant alloys in Table 14-15.

If the corrosion resistance of the 18 per cent chromium, 8 per cent nickel grade is required (Table 14-20) and is to be obtained by an arc-



600X

FIG. 14-29. Microcharacter Scratch across Ferritic White Cast Iron. These constituents differ widely in hardness, the carbide being about 7400 (9+ on Mohs's scale) and the ferrite (grey) about 1000 (Mohs: no. 5).

C%	Mn%	Si%	Cr%
3.35	0.90	0.66	23.4
Hardness		Wet-Sand	
Rc	BHN	Abrasion Factor	
44	381	1.00	



600X

FIG. 14-30. Microcharacter Scratch across Austenitic White Cast Iron. Note the faint slip bands that indicate work hardening of the austenite adjacent to the scratch. The poor abrasion resistance of this structure is surprising.

C%	Mn%	Si%	Cr%	B%
3.40	20.8	0.64	2.5	0.55
Hardness		Wet-Sand		
Rc	BHN	Abrasion Factor		
52	532	1.40		

Microhardness:

Carbides—K = 6100-6300

Austenite—K = 1200-1300

deposited overlay on ordinary steel, it is advisable to use a more highly alloyed welding rod, such as 309 (24 per cent chromium, 12 per cent nickel) or 310 (25 per cent chromium, 20 per cent nickel) to compensate for dilution of the weld by molten-base metal.

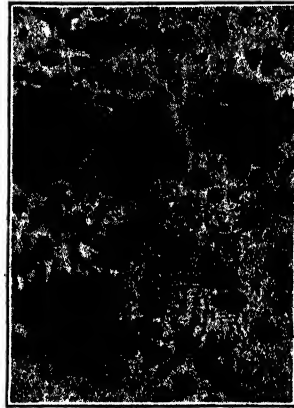
Tensile properties of the austenitic stainless steels are excellent, weld-metal values of 50,000-60,000 psi yield strength, 80,000-95,000 psi tensile strength, 30 to 45 per cent elongation, and 40 to 60 per cent reduction of area being obtainable. The difference between these figures and those for heat-resistant alloys in Table 14-15 is due chiefly to carbon content.

As the austenitic alloys are higher in thermal expansion and lower in heat conductivity than ferritic steels, thus fostering high residual



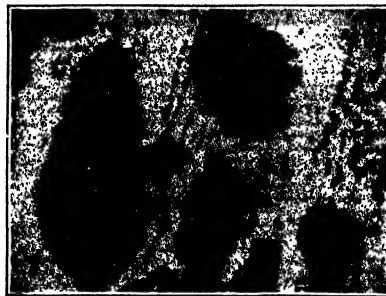
30X

FIG. 14-31.



150X

FIG. 14-32.



600X

FIG. 14-33.

C%	Mn%	Si%	Mo%	Rc	Abrasion Factor
3.60	2.64	2.07	8.93	67	0.54

Oxyacetylene weld deposit resulting in mixed structures: Graphite, austenite-carbide eutectic, and martensite or bainite. The abrasion resistance is somewhat impaired by the presence of graphite. Note diffusion of carbon from the weld into the SAE 1020 steel base, producing a zone of pearlite (not resolved at this magnification) adjacent to the weld junction.

stresses, it may be necessary to provide a heat treatment for stress relief after welding. This is difficult if intergranular corrosion is to be avoided, but may be partially accomplished at 800°F or obtained by

holding the columbium bearing grades at 1600° to 1650°F followed by air cooling.

The metallurgy of stainless steels is sufficiently complex to make advisable some study by both the engineer and the welder if corrosion resistant overlays are attempted.<sup>32, 36</sup>

### PEARLITIC STEELS

A steel containing 0.85 per cent carbon will transform to austenite when heated above 1360°F, but in the absence of other alloys it cannot retain this structure at room temperature even if drastically quenched. Quenching may produce a martensitic structure, but the slower cooling of normal weld deposits develops pearlite as the metal passes through the range from 1285° to 900°F. Many welding-rod deposits exhibit this behavior. If carbon content is lower, ferrite will probably be associated with the pearlite; if higher, free cementite in the form of a grain-boundary network may be expected. Hardness of the pearlitic deposit may be increased somewhat by the presence of cementite or by the occurrence of finer lamellas that are promoted by more rapid cooling or by moderate alloy contents. Abrasion resistance is ordinarily not improved, however.

Pearlite usually will range in hardness from 230 BHN (Rc 20) to around 400 BHN (Rc 42). Tensile strength follows a similar trend from 110,000 to 180,000 psi. Tensile elongation is usually below 15 per cent with a practical minimum of about 10 per cent. Weld deposits may be lower, and, if the cementite previously mentioned appears, elongation may fall below 1 per cent. Hard-surfacing deposits are seldom stressed in tension, however, the usual conditions being more likely to involve compression and impact. Pearlitic deposits have moderately high resistance to cracking under these conditions.



150X

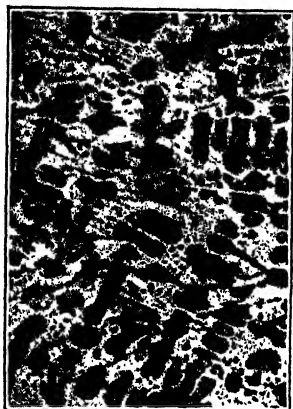
Fig. 14-34. Oxyacetylene Weld Deposit from an Alloy of Near Eutectic Composition. The constituents are carbide (white) and pearlite (gray; unresolved at this magnification). The fine-grained pattern of carbide and austenite, which is here transformed to pearlite, is known as ledeburite.

C%	Mn%	Si%	Cr%	Mo%
3.82	0.43	1.10	7.56	1.99
Hardness		Wet-Sand Abrasion		
Rc	BHN	Factor		
58	600	0.74		



## MARTENSITIC STEELS

Tool steels as commercially heat-treated have martensitic structures, which are modified slightly and toughened by tempering. If the same compositions are employed as welding rods, the different cooling rate will produce pearlite rather than martensite in the deposit unless



60×

FIG. 14-35.

C%	Mn%	Si%	Ni%	Cr%
3.43	0.72	0.62	1.58	1.54

Hardness	Wet-Sand
Rc	Abrasion Factor
53	0.90



300×

FIG. 14-36.

C%	Mn%	Si%	Cr%
3.40	0.62	0.68	1.55

Hardness		Wet-Sand
Rc	BHN	Abrasion Factor
50	477	0.87

**Pearlitic White Cast Irons.** The addition of the alloying elements is scarcely justified by the effect on abrasion resistance unless they are present in sufficient amount to suppress the pearlitic transformation. Note the difference in structure and performance when 4:5 per cent Ni is present with 1.5 per cent Cr (Fig. 14-2).

enough alloys are present to render it air hardening. Some tool steels, such as the high-speed and high-carbon 12 per cent chromium types, for example, are air-hardening even though the recommended heat treatments do not involve air cooling.

The alloys that produce martensitic weld deposits may be considered as modified tool steels. Adequate metallurgical knowledge and careful production control are necessary if the desired structure is to be obtained, though it may be achieved by many combinations of alloys. A check of structure is the best assurance of intended quality.

Weld deposits of martensitic steel represent probably the best combination of economy in first cost, hardness, strength, abrasion resist-

ance, good impact resistance, and relative toughness. Hardness ranges from 500 to 700 BHN (Rc 48 to 66), depending on the carbon content and the proportion of untransformed austenite that is retained after cooling. (This austenite is usually not disadvantageous for wear resistance as it has work-hardening properties.) Its strength is the highest of the hard-surfacing materials, some martensitic steels exceeding 300,000 psi in ultimate tensile strength. Weld deposits will probably range from 100,000 to 300,000 psi unless brittle constituents, such as free cementite, provide structural discontinuities. Abrasion resistance

TABLE 14-21. TYPICAL FERRITIC AND MARTENSITIC CHROMIUM STEELS AVAILABLE AS WELDING RODS

<i>Nominal Chemical Composition</i>			
Type	C%	Cr%	Others
<i>Ferritic</i>			
410 *	0.10	12	0.5% Mo
430	0.10	16	
442	0.10	18	
446	0.10	28	0.12% N
<i>Martensitic</i>			
501	0.10	2	0.5% Mo
502	0.10	5	0.5% Mo
505	0.10	9	1.5% Mo

\* May be martensitic if carbon is higher.

† Note that these are not A.I.S.I. type numbers.

*Properties of Type 2% Cr, ½% Mo Weld Metal \**

	Yield Strength, psi	Tensile Strength, psi	Elongation, %, 2"	R.A., %
As welded	120,000	125,000	8	
Stress-relieved	100,000	125,000	12	30
Air-cooled from 1250°-1400°F				
Annealed	45,000	85,000	28	65
Air-cooled from 1100°F—after furnace-cooling from 1550-1650°F				

*Approximate Properties of Types 5% Cr, ½% Mo, 9% Cr, 1½% Mo, and 12% Cr, ½% Mo \* Weld Metal—after Full Anneal*

	Yield Strength, psi	Tensile Strength, psi	Elongation, %, 2"	R.A., %
1550°-1650°F furnace—cool to 100°F, air-cool	40,000 50,000	750,000 850,000	25-35	55-65

\* Reference Chart on Alloy Welding, Arcos Corp., Philadelphia, 1945.

exceeds that of austenitic manganese steel, pearlitic steels, chromium-cobalt-tungsten alloys of comparable carbon content and toughness, and low-alloy cast iron of comparable hardness.

The ductility of martensite is low in comparison with that of engineering steels, but it is usually adequate for hard overlay requirements, where the base is expected to provide the toughness. Weld deposits may crack from cooling stresses or from heavy impact, but



FIG. 14-37. Hard-Surfacing a Grinding Mill Ring Used for Pulverizing Cement Clinker. About 75 lb of martensitic cast iron overlay were required for this 7-ft-diameter part. Up to 4500 hr of service have resulted from hard-faced rings.

only in exceptional cases does the bond between deposit and base fail, thus preventing loss of the overlay even when it cracks. A cracked deposit does not have maximum abrasion resistance, however.

Despite the similarity to tool steels, weld deposits do not achieve the same properties, especially toughness, because they represent cast rather than wrought metal. The process of hot working tends to break up masses of brittle constituents that otherwise would provide pathways for ready fracture.

For this reason, hard overlays should be designed for compressive stresses. As this is the usual status, relative brittleness in tension is seldom a handicap. Failures, in the form of spalling or cracking, are most likely to occur from shear stresses that accompany heavy impact.

Martensite may occur with austenite, pearlite, or both, in the same deposit. It is difficult to evaluate the merits of such mixtures; some are quite satisfactory. However, the presence of pearlite usually lowers the abrasion resistance and hardness of a martensitic structure. Austenite may lower hardness without adversely affecting wear. The tensile properties of mixed structures are usually inferior. It should be noted that improper application of rods of correctly balanced composition, as use of arc electrodes for gas welding or vice versa, may produce unintended structures of the mixed type.

### CAST IRONS

Ferrous alloys containing more than 1.7 per cent carbon are technically classed as cast irons, this being the maximum amount that can

be taken into solid solution by austenite under suitable conditions of heat treatment. The undissolved carbide is brittle and if distributed in continuity confers this quality on the alloy. Like steels, the matrix of cast irons may be austenitic, ferritic, pearlitic, martensitic, or mixed, with occasional appearance of the less common transformation products. The carbon in excess of that normal to the steel-like matrix may appear as graphite or as the iron carbide—cementite. If all of the excess carbon is graphitic, the iron is generally soft and has a *dark-gray fracture*; if cementite replaces the graphite, the iron is hard and has a glistening *white or silvery fracture*. Gray and white as used here are not only descriptive but have also wide acceptance as classification terms.

*Gray cast irons* are of little use for hard surfacing because they have very poor abrasion resistance. Under conditions of metal wear where the graphite flakes may act as a lubricant, or the flake cavities serve as tiny oil reservoirs that provide temporary protection against excessive friction during periods of boundary lubrication, gray cast iron may exhibit good wear resistance and antigalling properties. Its application in such cases can hardly be called hard surfacing, however.

*White cast irons* with low alloy content are more commonly encountered, as they can be made very inexpensively and produce a moderately hard weld deposit (400 to 440 BHN). Structurally, they consist of hard cementite masses set in a matrix of pearlite. They provide poor abrasion resistance under severe conditions, and, as they are also very brittle, their use is not recommended. So much of the total cost of hard surfacing is included in rod manufacture and weld deposition that a slight saving in alloy content is not economically justified. Good performance from pearlitic white cast irons is expected only when relatively soft abrasives are encountered; in general, they may be expected to behave like the chilled face of engineering iron castings.

Transition or mixed structures containing both graphite and cementite may be encountered; these are termed "mottled." Like gray iron, these have poor abrasion resistance, though they are somewhat harder.

Ferritic white cast iron is a rarity, as silicon, which is the element that usually creates ferrite in the presence of considerable carbon, is a strong graphitizer. Thus, high-silicon irons that are ferritic are also graphitic and gray in fracture.

#### AUSTENITIC WHITE CAST IRON

If enough nickel, molybdenum, manganese, or other austenitizing element, or a sufficient mixture of these, is added to a white iron-base

composition used as a welding rod, the resulting deposits, like Hadfield's manganese steel, will be austenitic after cooling to atmospheric temperature. They will contain hard carbides in a tough matrix. If, in addition, chromium or a similar carbide-forming element is included, the carbides will be hardened and will exhibit superior wear resistance. This combination appears to have excellent possibilities and has been exploited in a number of welding rods. The deposits are tougher than pearlitic white cast iron and also more abrasion-resistant, but they may not be superior in either of these properties to martensitic steel overlays. This, perhaps, is associated with selective wear of the softer austenite, permitting mechanical loss of the hard carbides before they are worn out. A loose abrasive is likely to produce this condition.

The strength of austenitic irons varies with the relative amounts of carbide and matrix; with about 2.7 per cent carbon, they may range from 40,000 to 90,000 psi ultimate tensile strength, with hardness between 400 and 600 BHN. Ductility is a property seldom determined or used for cast irons. It may be measured by precise methods, however, permitting interesting comparisons. Some austenitic irons have exhibited an elongation of about  $\frac{1}{4}$  per cent before fracture, contrasting with 0.04 per cent for a pearlitic white iron.

Although the term austenite should be reserved for iron-base alloys, substitution of "solid solution" for it would permit inclusion of many other materials, such as the cobalt base "Stellites," in a broad group. Possible alloy combinations are so many that it is difficult and misleading to generalize about their properties. However, there is some justification for saying that loading the austenite or solid solution with alloy elements beyond the limit needed to insure that no transformation occurs during cooling is uneconomical. An excess should be avoided unless some special property, such as heat or oxidation resistance, or corrosion resistance is required. Concerned chiefly with performance and cost, the engineer should scrutinize carefully the reasons for employing expensive high-alloy-content welding rods and, if practicable, make service tests to determine relative merits. Frequently, cost has been found to provide no index of value for abrasion resistance.

#### MARTENSITIC CAST IRONS

The possibility of undermining the carbides in austenitic irons by abrasion suggests that improvement should accompany a harder matrix. This has been reduced to practice in the martensitic irons. In the field of castings the best-known example is Ni-Hard, which has won an

enviable record in the field of wear. It consists essentially of about 3 per cent carbon,  $4\frac{1}{2}$  per cent nickel, and  $1\frac{1}{2}$  per cent chromium,<sup>39</sup> with minor amounts of other elements common in cast iron. The chromium has hardened the carbides and suppressed the tendency for them to graphitize, while nickel prevents the pearlite transformation on cooling but is not in sufficient amount to stabilize austenite in the martensitic transformation range. The result is a collection of very hard carbides in a hard martensitic matrix (Fig. 14-2).

Because of the nice balance required (pearlite formation, graphitization, and excessive austenite retention must all be avoided), this material is difficult to manufacture. It has its counterpart in hard-surfacing alloys, which similarly require close technical control in manufacture. However, when the properly balanced alloy is obtained, it provides maximum abrasion resistance compatible with moderate cost.

Martensitic irons range from 500 to 750 BHN in hardness. The higher values are difficult to measure, and Rockwell C scale readings, which range upwards from C 52, are generally more satisfactory. Ultimate tensile strength for castings is around 30,000 to 40,000 psi, which may be nearly doubled by a low-temperature heat treatment. Surprisingly, the heat treatment usually decreases abrasion resistance while it may increase hardness. This is an excellent example of the fallacy of assuming a direct and universal correlation between hardness and wear resistance.

Other elements than nickel and chromium may be used for martensitic irons, though this is the least expensive combination. The elements present are less important than their balance. As this type material may easily be the most useful of the hard-surfacing group for severe abrasion and moderate impact, the engineer should consider having the deposited structure checked where large amounts of welding rod are to be used.

The foregoing description of hard-surfacing alloys is not complete; to make it so would require too much space for this book and the use of too many items of dubious or incomplete data. It may leave the engineer at a loss to determine the relation between performance and structure previously described and the trade names that identify the welding rods offered to him. This undesirable feature is recognized, but no easy remedy is available. Some manufacturers recognize and understand this dilemma and maintain a staff of service engineers who are competent welders and who also understand the metallurgical and wear

problems involved. They offer instruction in deposition techniques and an experienced analysis of the service factors that must be considered. As hard surfacing is not yet a complete science, the consultation of such men is a valuable supplement to information of the type included here.

#### WELDING TECHNIQUE

It should not be necessary to describe here the well-known details of welding practice, but some of the features peculiar to hard facing are worthy of mention. Thick deposits, surface smoothness, cracking tendencies, and base metal damage may require special consideration.

Thick overlays are usually required when severe wear of a part makes necessary the deposition of much metal to restore the original dimensions. Thick protective deposits are infrequently indicated. For economy in such cases it is customary to build up the worn area with a high-strength steel welding rod (pearlitic steels are generally satisfactory) to almost the finished dimensions and to add the actual protective material as the final layer.

Surface smoothness, which is sometimes demanded by service considerations, depends on the deposited material, the method of welding, and the skill of the welder. The hard-setting type of tungsten carbide will obviously provide a rough surface unless it is completely submerged in added matrix alloy. Similarly, the composite tungsten carbide deposits, if the carbide particles are not very fine, will leave a surface that if not originally rough may be expected to become so by differential wear. Where the carbide particles function as cutting teeth in service, as in oil-well drilling, the roughness is an asset, but for smooth wearing surfaces, as in guides or plows, a more homogeneous deposit is to be preferred.

Electric-arc deposits, because of the individual beads that characterize them, are somewhat rougher than oxyacetylene deposits. Not all torch deposits are smooth, however, the nature of the material being important. The presence of massive carbides, which appear necessary for maximum wear resistance in some alloys, usually reduces the flowability of the molten deposit, making it more difficult to achieve smoothness. Those alloys that are featured for high fluidity by the manufacturers, when oxyacetylene-deposited, may be expected to produce the smoothest deposits. Some of these will flow and "wet" the base metal so readily that a relatively uniform deposit only  $\frac{1}{32}$  in. thick is possible.

The tendency for weld metal to crack is one of its most disconcerting features.<sup>40</sup> In the wet-sand abrasion test previously described the presence of cracks characteristically increases the rate of wear, though in some service applications their effect is negligible. If the cracks are few and proceed normal to the surface, stopping at the tougher base as they usually do, they need cause no concern about loss of the deposit itself. The bond between weld and parent metal is almost always so strong that fracture occurs elsewhere. A network of cracks in a thick and brittle deposit may cause loss by spalling of the outer portions, however.

Stresses that develop from hindered expansion or contraction of the weld and base are the primary cause of cracks. The steep temperature gradients incident to welding are responsible. Even uncracked welds may contain high residual stresses that may seriously affect service behavior by producing a delayed rupture or perhaps warping.

Most structural welding alloys are relatively weak at high temperatures or have a low yield strength at atmospheric temperature. Such materials permit stress relief by plastic flow and minimize cracking. The hard-surfacing alloys, in contrast, usually are quite strong at elevated temperatures and relatively brittle under all conditions. Thus, they crack rather than yield when thermal stresses exceed their elastic tensile strength. The properties of the base metal may be of great importance; if sufficiently ductile, it may deform instead of the weld and thereby prevent cracking. If the carbon content of the base is high (above 0.40 to 0.60 per cent) \* there is danger of making it brittle or of cracking it by the welding operation. Such materials should be *heated and cooled slowly*, and a stress-relieving heat treatment after welding is desirable to remove residual stresses.

An analysis of the temperature and stress conditions during welding of an overlay may clarify the stress problem. If it is assumed that the base is stress-free initially, the application of the welding heat will cause expansion of the surface zone adjacent. This expansion will develop compressive stresses in this area, which, after the elastic limit of the material at the temporary temperature is exceeded, will *upset in compression*. This plastic flow is in the form of local shortening. When subsequent cooling occurs, the thermal contraction will reverse the stresses. Now cold plastic flow will be required to restore the original dimensions, or the material must rupture or warp. If the alloy is suffi-

\* In some cases even lower carbon contents may cause difficulty.<sup>40</sup>



ciently ductile, flow above the yield strength will absorb the contraction tendency, leaving residual tensile stress at about the elastic-limit level, however. If ductility is lacking, as with many high-carbon steels, especially if the welding has also caused hardening, the ultimate strength may be exceeded easily, and cracking may result. Passing through the critical temperature range adds other expansion factors that may complicate the situation. Thus, it appears why ductile low-carbon steels are preferred as bases for hard surfacing.

The fact that hot upsetting occurs readily because the strength is low at high temperatures, with ductility usually high, and the reverse tensile stresses appear under conditions of lower ductility because of lower temperature is an unfavorable feature that should not be forgotten in welding.

Once the overlay is in place, it may be considered a part of the base. It is in a molten state when cooling and contraction begin, however, which means that it will try to contract perhaps 2 per cent in returning to room temperature. If the temperature of the base is much different, it will contract less and thereby restrain the welded layer, producing the same sort of tensile stresses previously described. With oxyacetylene heated metal, especially if careful preheating was employed, the temperature gradients may be small, with attendant low residual stresses. With arc welding and without preheating the reverse is true, and cracking is invited. *Avoidance of thermal gradients* is thus the most important preventive of cracks.

The added plasticity conferred by high temperature may be made to serve a useful purpose, especially near the melting point. Within limits, the deposits can be shaped by hammering, scraping, or hot filing, whereas they usually cannot be shaped at atmospheric temperatures except by grinding.

Surface peening tends to produce compressive stress. If the deposit is of low yield strength and is quite ductile, as are the austenitic steels, the residual tensile stresses from welding may be neutralized by hammering the surface. This is frequently standard practice after depositing manganese steel; peening may follow the addition of each new bead.

If latitude in selection of the base to be hard-surfaced is possible, it is generally desirable to choose a medium- or low-carbon steel, the strength required governing the choice. Practically any ferrous alloy can be hard-surfaced, however, gray cast irons and high-speed steels being the most difficult. The latter are very susceptible to cracking, and, as they approximate the martensite-steel weld materials in per-

formance, there is little reason to hard-face them. High-melting-point nonferrous alloys can also be hard-surfaced, but, if the melting point is below 2000°F, the attempt is not advisable. Copper, brass, and bronze thus offer serious difficulty. Monel metal can be hard-faced easily, however.

Similar expansion coefficients tend to minimize thermal stresses. Thus, it is advisable to match them approximately in weld and base metal. For practical purposes, the important distinction lies between ferritic and austenitic alloys, the former expanding about 1.5 and the latter about 2.0 per cent between room temperature and 2000°F. Austenite transformation adds an important volume change, also. It may be enough to cause cracking itself, in some circumstances.

#### COST OF HARD SURFACING

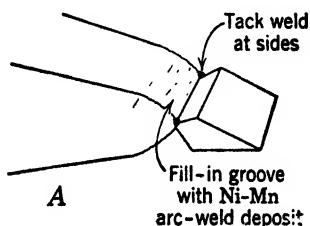
It would be desirable to include data that an engineer could use for estimating the cost of hard surfacing on a prospective job. Unfortunately, inclusion of figures from experience would probably be disappointing in application to new work, chiefly because of the variables involved. The cost of rods, oxygen, acetylene, and electricity can be readily obtained. Welding skill and the nature of the work vary so widely, however, that labor costs, which may overshadow the other factors, cannot be satisfactorily predicted. It must suffice to suggest that the cost per pound of rod used be obtained experimentally if a basis for estimating on an important project is required. One pound of electric welding rod will usually coat 20 sq in. about  $\frac{1}{8}$  in. thick; gas welding rod will cover about 24 sq in.

#### COMPOSITES

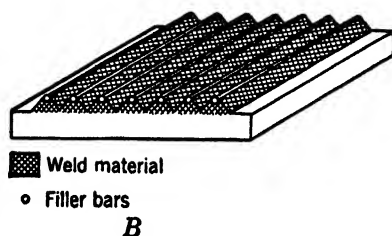
There are focal areas of wear in some equipment where metal is removed too fast for satisfactory performance of thin weld deposits. Heavy inserts of the appropriate material may be more practical. Thus, in power-shovel buckets and dippers it is customary to provide detachable teeth of austenitic manganese steel; these in turn may have their points renewed by welding on replacement wedges of manganese steel, which are available as small castings or as longer bars that may be cut to the length desired. A variety of such "filler bars" permit rebuilding of badly worn parts, such as crusher jaws, grizzly bars, and the like (Fig. 14-38).

Some problems are best solved by inclusion of a hard insert in an otherwise softer and tougher casting. The composite brake shoe in Fig. 14-39 is an example. A number of metallurgical expedients are

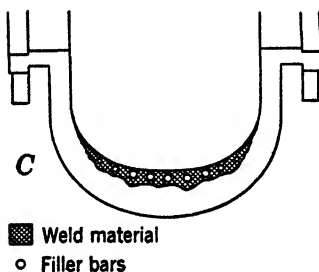
practicable for similar needs, the most widely used being perhaps the armored surface provided by chilling cast iron. Rapid cooling of the



Method of Repointing Worn Dipper Teeth of Austenitic Manganese Steel.



Method of Rebuilding Crusher Jaw with Nickel-Manganese Steel Filler Bars and Arc-Weld Deposits.



Method of Building Up Worn Pump Shells with Nickel-Manganese Filler Bars and Arc-Weld Deposits.

FIG. 14-38.

chilled area in the mold results in a zone of hard white cast iron, while the other more slowly cooled portions of the casting graphitize to produce a soft strong machinable gray iron. Most of the railway-freight-car wheels in service have this combination structure.

Some manufacturers of wear-resistant alloys are equipped to provide castings, castings with inserts, composite castings with thick wear-resistant areas as integral parts, or welding rods with which the user of equipment may apply the hard coatings himself. Each of these possibilities should be examined for economy and service merit.

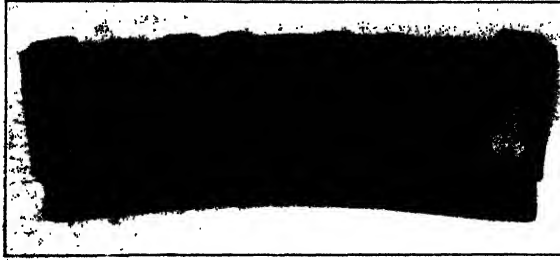


FIG. 14-39. An Example of a Composite Casting Containing Hard Inserts, Cast into Place in a Softer Matrix, That Is Controlled for Frictional Properties. This is a railway-locomotive brake shoe. The insert arrangement is more satisfactory than hard surfacing in this case.

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## Sprayed Metal

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Metal may be sprayed onto almost any surface to form a metal layer. This process, known as metallizing or metal spraying, was originated by Schoop and introduced into the United States about 1920.

The metallizing process is being used today predominantly for maintenance, repair, and rebuilding of machinery. It is also being used to

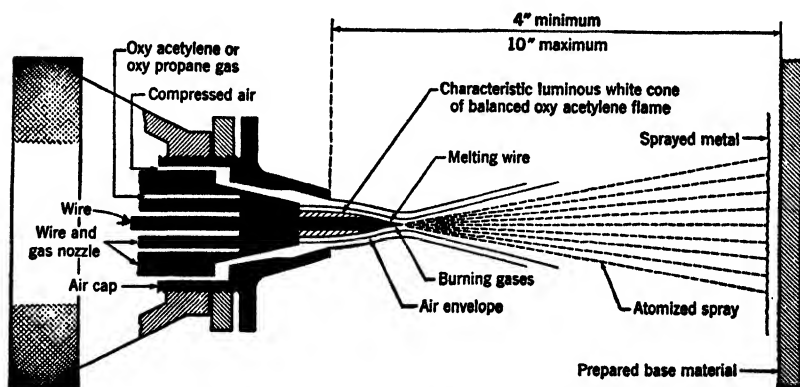


FIG. 15-1. Wire-Nozzle and Air-Cap Cross Section—Meteco Metallizing Gun.

a greater extent than ever in the manufacture of new products, particularly as a means for producing new corrosion-resistant materials.

In the metal-spraying process, the metal is melted and impelled in finely divided form against the object to be coated. A number of different types of equipment have been developed for this process. Depending on the equipment used, the metal may be supplied in the form of either wire or powder and may be melted either by an electric-

arc or an oxyacetylene flame. The most practical metallizing guns today use metal supplied in wire form and utilize a flame for melting. The flame is usually oxyacetylene, but other gases are sometimes used in place of acetylene.

Considerable development has been done on metallizing equipment in recent years so that reliable equipment is now available both for hand use and for machine mounting for production use. Figures 15-1 and



FIG. 15-2. Production Metallizing Gun.

15-2 illustrate modern metallizing guns. These guns are fully automatic in operation and feed the metal wire at a predetermined controlled speed.

#### USE FOR MACHINE-ELEMENT MAINTENANCE AND REPAIR

The largest single use for sprayed metal today is for building up machine elements. This includes maintenance and repair and also salvage of mismachined parts. Because the structure of sprayed metal is porous, it forms an excellent bearing material either in hard metals on shafts or soft metals in sleeves, and for this reason it is used most extensively on bearing surfaces. The machine element is first prepared by undercutting and some form of roughening and then sprayed to a dimension larger than the finished size. The sprayed metal may then be machined or ground.

A few typical uses are salvage by building up parts such as processing rolls, restoring steam cylinder bores, building up armature shaft

bearings, building up steam-turbine shafts at the packing area, and resizing shafts for wheel-press fits and rebuilding crankshafts.

### USE FOR CORROSION RESISTANCE

Metal-sprayed aluminum and zinc are used very extensively to prevent corrosion on iron and steel. Typical uses include air-cooled aircraft-engine cylinders, vapor-spray degreasers, bridges, lock gates, water storage tanks, boat parts, marine hardware, pole hardware, and transformer cases.

Metallizing is used with or without paint or other organic finishes. Metallized zinc and aluminum form an excellent base for paint. Metallizing with aluminum and special combinations of nickel-chromium alloys and aluminum are now used extensively for preventing heat corrosion on heat-treating vessels and the like.

### USE FOR NEW MANUFACTURED PRODUCTS

Sprayed metal is being used in the new manufacture of many machine elements for uses similar to those originally developed as maintenance applications. It is used primarily where its excellent bearing and wear-resistant qualities are of advantage or for corrosion-resistant purposes. It is now being employed more extensively to provide hard-wearing surfaces on aluminum alloys to extend the use of light metals to machine elements.

Metal-sprayed coatings are also being used for corrosion resistance on small manufactured articles, particularly since the rapid expansion in the field of tumbling barrel metal-spray coating. Metallizing is used extensively for the manufacture of carbon brushes and resistors to provide a means of soldering to the carbon. It is also used in the manufacture of electrolytic condensers, the condenser plates being manufactured from cloth tape by metallizing with aluminum. Glass is metallized for a number of industrial applications. Sprayed copper makes it possible to solder-seal glass as in meter windows. Sprayed aluminum is used on glass to form electric heaters and also to provide a reflecting surface on reflectors.

## NATURE OF SPRAYED METAL

### A NEW ENGINEERING MATERIAL

Sprayed metal is a new metal produced as the result of the metal-spraying operation. It is chemically and physically different from



the original wire-sprayed. Considerable emphasis is required on this point, as sprayed metal is a new engineering material.

The conditions under which the metal is sprayed with modern equipment are subject to complete control. Therefore, sprayed metal can be controlled and standardized. Entirely different structures can be obtained using the same wire under different or abnormal spraying conditions.

The structure of normal sprayed metal results from spraying under "normal" conditions, such as would be obtained in a manufacturing or



Fig. 15-3. Sprayed Iron at 400 $\times$  Unetched.

repair shop when equipment is operated in accordance with the manufacturer's instructions. Although a great many variations can be performed in the laboratory to produce different results, at the present time most such variations defeat the general purpose and utility in commercial metallizing.

Normal sprayed metal has a structure made up of a great many layers of small scalelike particles which overlap and interlock with each other. These scales are generally parallel to the surface sprayed, although they are very irregular. A typical sprayed-metal structure is shown in Fig. 15-3, which is a photomicrograph of sprayed iron at 400 $\times$ , unetched.

Sprayed metal is usually bonded to the base metal by mechanical interlock. For this reason, the base material must be roughened prop-

erly. The type of roughness for bonding sprayed metal can be produced on steel by grit-blasting with angular steel grit. Heat is occasionally used for bonding, particularly for bonding on glass.

The mechanism of attachment of particles to each other to form the structure is not known completely. There is a great deal of mechanical interlock between particles, and in some cases there is a small

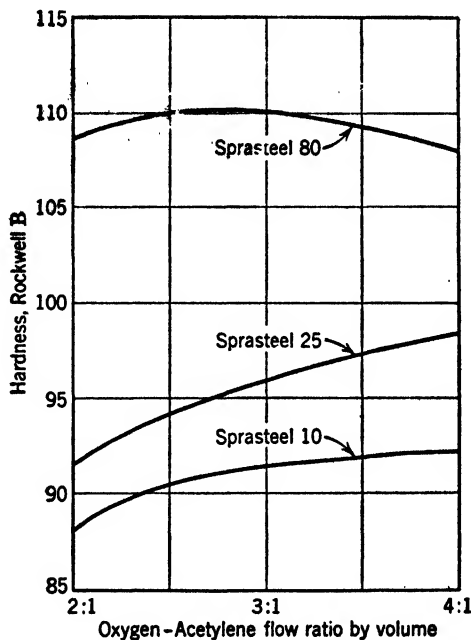


Fig. 15-4. Effect of Gas Ratio on Hardness.

amount of welding at some points between particles. There also appears to be oxide cementation between particles. The physical properties of sprayed metal, therefore, include the properties of the metal particles, the cohesiveness of the particles or the strength of particle attachment, the degree of porosity of the structure, and the effect of the oxide content. There are, of course, a number of other factors, but these appear to be the primary ones.

Hardness tests, such as Rockwell, will measure primarily a combination of the hardness of the metal particles, the degree of porosity of the coating, and the effect of the oxide content. The strength of particle attachment has a relatively lesser effect on hardness.

Tensile-strength measurements, however, measure the strength of

particle attachment almost entirely. Because sprayed metal shrinks somewhat in its application, initial stresses are set up internally.

#### THE EFFECT OF THE SPRAYING TECHNIQUE ON THE PROPERTIES OF SPRAYED METAL

The properties of sprayed metal are affected by the spraying technique and the other conditions under which the metal is applied. For-

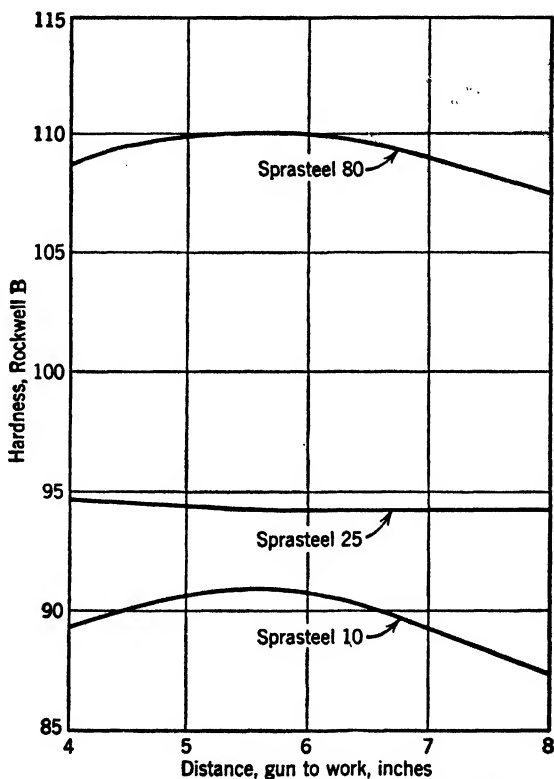


FIG. 15-5. Effect of Distance on Hardness.

tunately, the variations in physical properties are within reasonably narrow limits under normal spraying conditions. Where required, extra controls such as flow meters for the gas and oxygen can be installed to reduce the variation in resulting physical properties to almost any desired minimum.

An unbalanced gas-oxygen ratio of the melting flame will cause a variation in the physical properties, such as hardness. Figure 15-4

shows the effect of off-balance gases on the hardness of sprayed carbon steels. These are laboratory tests and represent a greater variation in gas-oxygen ratio than would result even in ordinary uncontrolled shop operations.

The distance of the gun to the work will also affect the physical properties, such as hardness, but in this case an extremely small dif-

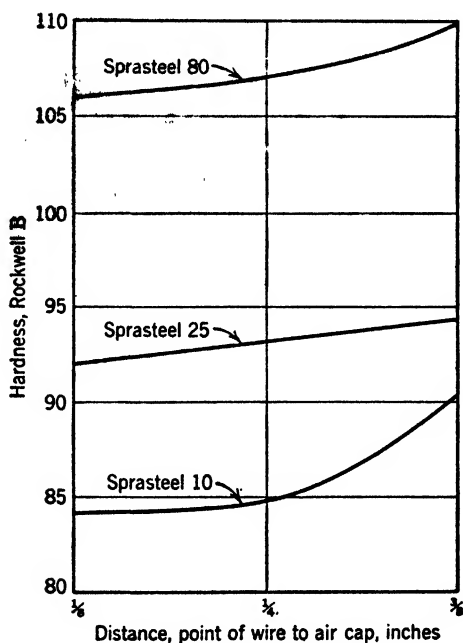


FIG. 15-6. Effect of Length of Wire Tip on Hardness.

ference results from a wide variation in distance. This is illustrated by the curves in Fig. 15-5.

The speed of the wire feed also affects the physical properties. In operating the gun, the faster the wire feed, the further the unmelted tip of wire will extend from the nozzle into the melting and atomizing zone. Figure 15-6 illustrates the effect of wire speed as measured by the length of the wire-tip extension from the nozzle on the hardness of the sprayed coatings.

There are, of course, a number of other conditions which affect the physical properties, and some of these are represented in Table 15-1 which shows the effect of variations from normal spraying conditions on the hardness of three different carbon steels.

The angle of spray impingement to the work surface has a pronounced effect on the physical properties and structure of sprayed metal. In normal spraying it is considered best to spray as nearly perpendicular to the work as possible. Angles from perpendicular to approximately  $45^\circ$  have relatively little effect on either the structure or the physical properties. Angles less than  $45^\circ$  with the work surface rapidly change the structure with a decrease in the angle and produce

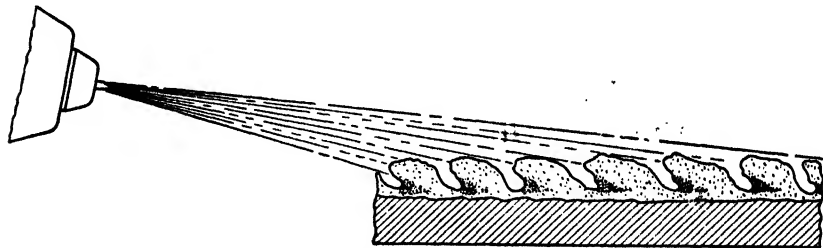


FIG. 15-7. Shadow Effect When Spraying at Steep Angle.

what is known as the "shadow effect." When spraying is at steep angles, the particles which initially adhere form spaces beyond them (shadows) which cannot be reached by the next particles striking the work. This tends to build up a very porous and wavy structure. Figure 15-7 illustrates diagrammatically how this effect is produced, with a surface like sand dunes.

TABLE 15-1

Special Condition	Rockwell Hardness		
	Sprasteel 10	Sprasteel 25	Sprasteel 80
Normal (acetylene gas)	B 91	B 94	C 38
High-pressure propane, 38 lb	B 94	B 101	C 41
High-pressure acetylene, 25 lb, air, 70 lb	B 87	B 103	C 41
Sprayed hot, work preheated to $700^\circ\text{F}$	B 95	B 102	C 40
Propane at 20 lb	B 90	B 93	C 35
High air pressure, 80 lb, acet., 15 lb	B 85	B 97	C 32
Normal spray at $45^\circ$ angle	B 86	B 94	C 34

A special phenomenon associated with this shadow effect is the production of what are known in the metallizing industry as "hard rings" at the shoulders of shafts inlaid with sprayed metal. Figure 15-8 shows a section through a shaft with a high shoulder and triangular-shaped hard rings at the shoulders. These rings occur next to the shoulder and are usually dark, particularly with carbon steels, and are quite difficult to machine. These rings are produced if the spray-

ing is done perpendicular to the shaft axis. They can be reduced or eliminated in actual work by, first, hand spraying into the corners to build up heavy round fillets before the gun is mounted for spraying perpendicular to the shaft axis. However, structures somewhat similar to these cannot always be avoided, particularly when small inside diameters such as ball-bearing sockets are sprayed. The "hard rings" frequently appear soft on a Rockwell machine owing to their extra porosity, but they dull a machining tool and thus appear hard because of their oxide content.

These hard rings result from a geometric pattern built up by the manner in which the particles have struck the surface. This is a special case of the shadow effect, which has occurred on the vertical faces of the shoulders. The manner in which this occurs on each layer of this peculiar structure may be seen in Fig. 15-9 which shows a section through a "hard ring" magnified 10X and etched.

This structure contains a greater per cent of oxide, since in normal spraying most of the oxide is fine and is blown away, whereas the porous structure produced by the shadow effect collects and retains a high percentage of oxide.

Stainless steels form a much less visible "hard ring" than carbon steels, but the physical nature of the structure is the same.

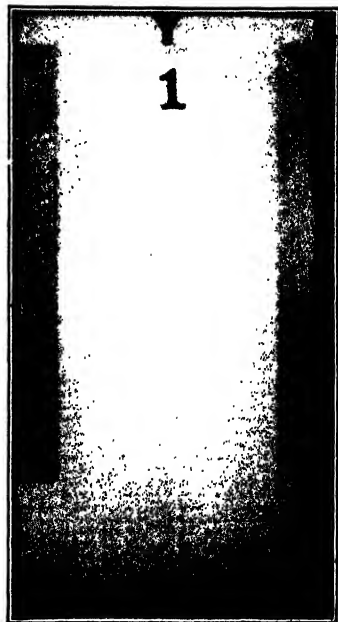


FIG. 15-8. "Hard Ring" at Shoulder.

#### BONDING SPRAYED METAL TO THE BASE

With some exceptions, sprayed-metal coatings are attached to the base by a mechanical bond, and the metallizing process is generally used as a cold process, where the temperatures are a few hundred degrees at most, and no welding takes place.

Recently it has been discovered that certain alloys high in molybdenum will bond strongly to smooth metal when sprayed directly thereon. The bond obtained is very strong to practically all metals

except to copper-base alloys. An alloy for this purpose is marketed as "Sprabond" and is used primarily as a bonding undercoat 0.002 in. thick to bond other sprayed metals to smooth surfaces. The bond between the sprayed molybdenum alloy and the base metal is of a physicochemical nature. Bond strengths obtained by this method compare approximately with Fusebond, taps 2 and 4, Table 15-2.

Sprayed metal can be applied to nonmetallic bases such as wood and plaster on either porous or roughened surfaces. It can be applied

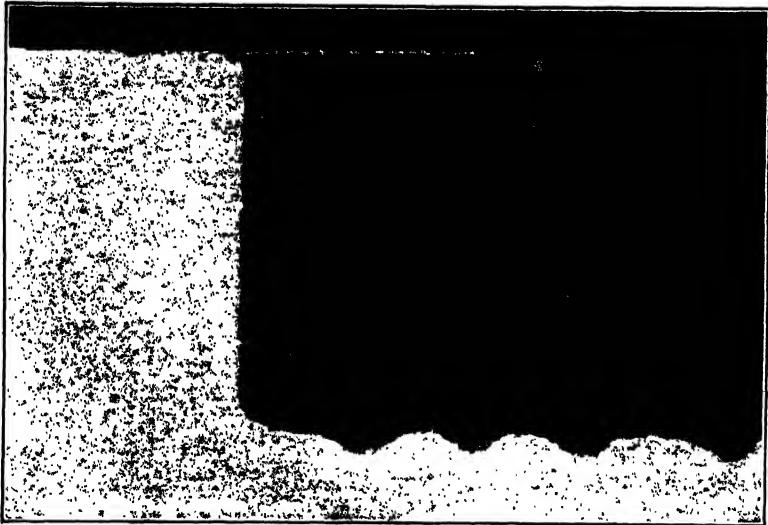


FIG. 15-9. "Hard Ring" 10 $\times$  Etched.

to glass quite successfully by heating prior to spraying. Most applications for metallizing, however, are for bonding sprayed metal to metal surfaces.

The most common method of preparing metal surfaces for metallizing is by blasting with angular steel grit. Mechanical roughening by machining is quite commonly used, particularly on machine elements. Turning a very rough and broken thread is often a satisfactory preparation. A special roughening tool has been developed, which will also produce a satisfactory prepared surface. A very strong bond can be obtained on machine elements by grooving and applying this tool to produce a surface such as is shown in Fig. 15-10.

The Fusebond Process of electrical surface preparation has also been used quite extensively in recent years. The surface produced in

this manner is illustrated in Fig. 15-11. This method consists in depositing a nickel alloy and fusing it to the base in a thin layer with a

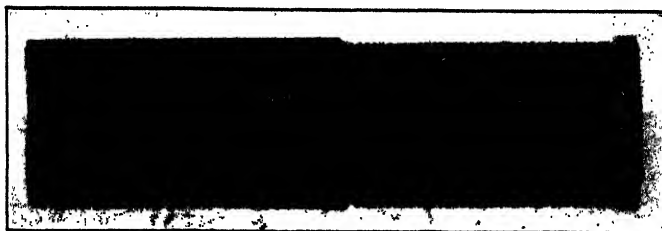


Fig. 15-10. Shaft Grooved and Prepared with Metco Shaft Preparing Tool.

very rough surface. The rough surface provides the ideal anchorage for sprayed metal. The Fusebond Process is carried out by connecting



Fig. 15-11. Surface Produced by Fusebond Preparation.

a special transformer to the work and to a multiple electrode holder and then stroking the work with the electrodes.

Heating the base metal is sometimes used as a means of securing bond.



TABLE 15-2. RELATIVE BOND STRENGTH OF DIFFERENT METHODS OF PREPARATION FOR VARIOUS BASE MATERIALS

For Sprasteel Coatings

Method of Preparation	Bond Factors (See Table 15-3) Base Material					
	Cold-Finished Steel	Alloy Steel Hardened to Approx. 52 Rock. C	Steels Hardened to Approx. 67 Rock. C	Bronze	Cast Gray Iron	2S Aluminum
Fusebond, fine grain, taps 2 and 3	4	3	5	1	4	1
Fusebond, medium, taps 1 and 3	6	5	7	1	7	1
Fusebond, coarse, taps 2 and 4	9	8	9	1 to 5 *	9	2
Fusebond, taps 2 and 4 over 24 pitch full thread	10	10	10	1 to 6 *	10	2
Fusebond taps 2 and 4 turned off to not less than 0.008 in. from base	7	7	7	1 to 3	7	1
Grit blast G16 steel at 90 psi or for base hardness exceeding 50 Rock. C.						
Metcolite C at 90 psi	6	4	2	3	4	3
Full Meteco Method	10	Not applicable	Not applicable	10	10	6
Meteco Shaft Tool over 24 pitch 75% thread	10	Not applicable	Not applicable	10	10	6
Rough thread, 24 pitch full depth	8 *	1	Not applicable	6 *	9 *	2

\* Field experience indicates considerable variation in results depending on base-material analysis and operator technique. Tests should be made.

TABLE 15-3. STRENGTHS FOR BOND FACTORS IN TABLE 15-2

Factor	Approximate Shear Strength, psi by Test	Approximate Tension Strength, psi by Test
10	10,000 & over	3,000 & over
9	9,000-10,000	2,400-3,000
8	8,000- 9,000	2,000-2,400
7	7,000- 8,000	1,800-2,000
6	6,000- 7,000	1,600-1,800
5	5,000- 6,000	1,400-1,600
4	4,000- 5,000	1,200-1,400
3	3,000- 4,000	1,000-1,200
2	2,000- 3,000	800-1,000
1	Less than 2,000	Less than 800

The bond factors given in Table 15-2 are determined according to this table. If shear and tension values indicate different bond factors, the lesser factor is used.

The bond strength between the sprayed coating and the base is often the critical factor in machine-element work. This would be true in applications such as building up crankshaft throws and main bearing sections. The bond strength is even more important on flat surfaces and inside diameters. Table 15-2 gives relative bond strengths for different methods of preparation of base materials. Table 15-3 interprets the bond factors in terms of shear and tension strength of bond.

### PHYSICAL PROPERTIES OF SPRAYED METAL

**Hardness.\*** As mentioned previously, hardness readings, such as Rockwell, measure several properties of sprayed-metal coatings, including porosity and particle attachment. For this reason, hardness readings are not comparable with solid metal. In all cases of lubricated wear, the sprayed metal will outwear solid metal. In most cases of abrasive wear, the particle hardness, rather than the Rockwell reading, would be comparable to solid metal, except for cases where cohesion of particles is very poor. For this reason, wear resistance is generally much higher than indicated by hardness readings, and these readings can be used only for comparing one type of sprayed metal with another. Table 15-4 gives typical hardness and analyses of normal sprayed metal.

**Shrink.** Sprayed metal shrinks progressively as it is applied in thin layers, so that a complex series of internal stresses is built up in the final coating. If sprayed metal is applied to a thin plate, it will tend to warp so that the edges lift up toward the metallizing gun. Where heavy coatings are applied to shafts, cracking sometimes occurs, particularly where a metal with a high shrink factor is used. This shows that it is possible to build up the internal stresses to as high as the ultimate strength of the material. It is, therefore, obvious that the actual tensile strength remaining in the coating is the difference between its potential strength and the amount of stress set up by shrinkage. It is, therefore, just as important to use a metal which has a small amount of shrink on application as to use a metal which has a high tensile strength, and both factors should be taken into account. To avoid building up the stresses, it is also important to have as great an elongation as possible.

No absolute quantitative means has been worked out for measuring the shrink of sprayed metal, since it progresses layer by layer. A num-

\* See Chapter 14 for an extended discussion of hardness and wear resistance.

TABLE 15-4

Hardness of Sprayed Metals

Metal	Rockwell Hardness	Metal	Rockwell Hardness
Metco Aluminum	H-72	Metco 1	B-78 to B-80
Sprababbitt A	H-88	Metco 2	C-31 to C-33
Sprababbitt B	H-11	Sprairon A	B-79 to B-81
Sprabronze C	F-67 to F-69	Sprasteel 10	B-89 to B-91
Sprabronze M	F-75 to F-76	Sprasteel 25	B-83 to B-95
Sprabronze P	F-73 to F-74	Sprasteel 40	B-96 to B-98
Sprabronze T	F-78 to F-79	Sprasteel 80	C-37 to C-39
Metco Copper	F-78 to F-79	Sprasteel 120	C-30 to C-32
Metco Monel	F-78 to F-79	Metco Tin	H-10
Metco Nickel	F-86 to F-88	Metco Zinc	H-46

Type Analysis

	Aluminum	Tin	Antimony	Copper	Lead	Zinc	Nickel	Carbon	Manganese	Silicon	Phos.	Sulfur	Chromium	Cobalt	Iron	Arsenic
Aluminum	99															
H.P. Aluminum	X															
Sprababbitt A		89	7.5	3.5	0											
Sprababbitt B		12	15	0.025	Bal.		0.10									1
Sprabronze C				90		10										
Sprabronze M		0.95		57.79		40.35	0.03	0.03	0.03						0.85	



ber of empirical test methods have been used, however, for specific thicknesses, and they all show consistent results as regards the relative amount of shrink between various sprayed metals. Table 15-5 shows the results of one of these shrink test methods.

**Tensile Strength.** Of necessity the tensile-strength figures show the net remaining strength in the test specimen. Specimens for tensile-

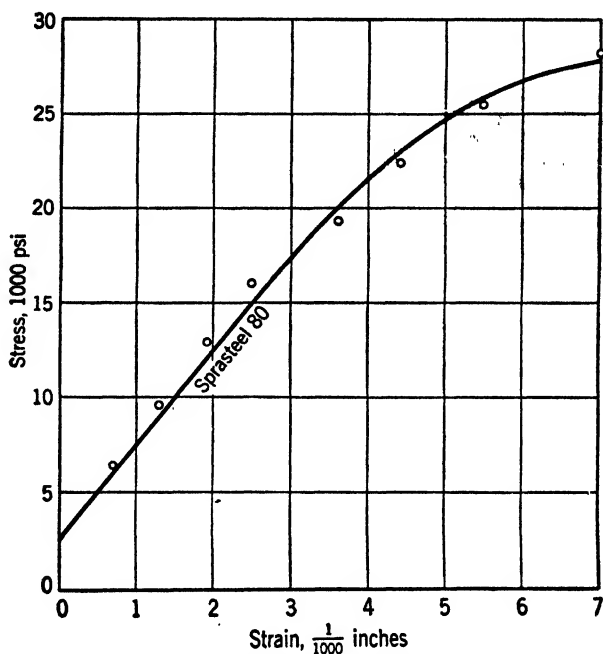


FIG. 15-12. Typical Stress-Strain Curve of Sprayed Steel.

strength figures given here were prepared by spraying onto steel cores and then machining the cores out so that the resulting tensile specimens were hollow tubes made entirely of sprayed metal. Tests made in this manner are quite consistent. The typical stress-strain curve of sprayed carbon steel is shown in Fig. 15-12. It may be noted that the material is brittle and has a stress-strain curve more characteristic of cast iron than of steel. Table 15-6 gives typical tensile strengths of a number of sprayed metals.

**Specific Gravity of Sprayed Metal.** Since sprayed metal is porous, the specific gravity of sprayed metal is less than that of solid metal. The specific gravity varies from metal to metal from about 83 to 90 per cent by weight of the original wire.

## SPRAYED METAL FOR CORROSION RESISTANCE

## CATHODIC COATINGS

Metallized coatings of metals which are cathodic electrically to the base metal are good only in heavy coatings on machine-element work. For instance, stainless steel is used quite extensively for pump shafts and steam-turbine shaft inlays. Brass, bronze, nickel, stainless steel, copper, and such are of no use in *thin* coatings, since the base would be rapidly attacked through the pores of the coating.

TABLE 15-5. COMPARATIVE SHRINK OF SPRAYED METALS

Metal	Shrink, in. per inch
Sprairon A	0.009
Sprasteel 10	0.008
Sprasteel 25	0.006
Sprasteel 80	0.0014
Sprasteel 120	0.0043
Sprabronze T	0.010
Metcoloy 1 (stainless)	0.012
Metcoloy 2 (stainless)	0.0018

TABLE 15-6. TENSILE STRENGTH OF SPRAYED METAL

Metal	Ultimate Strength, psi	Strain at Ultimate, % Increase in Length
Metcoloy 1	30,000	0.27
Metcoloy 2	40,000	0.50
Sprairon A	28,000	0.25
Sprasteel 10	30,000	0.30
Sprasteel 25	34,700	0.46
Sprasteel 40	28,800	0.37
Sprasteel 80	27,500	0.42
Sprasteel 120	23,100	0.61
Metco Aluminum	19,500	0.23
Metco S.F. Aluminum	37,000	0.54
Sprabronze P	18,000	0.35
Sprabronze T	13,000	0.51
Metco Zinc	13,000	1.43

For limited use, it is possible to seal up the pores of cathodic coatings such as stainless steel. Hydraulic ram plungers, for instance, can be sealed with tung oil or linseed oil mixed with a drying agent. Objects small enough to handle in dipping tanks can be sealed quite satisfactorily for low-temperature use. The procedure is to apply a thin un-

dercoating of sprayed tin, followed by a coating of the cathodic metal (bronze, Monel, and so on) and then dip in molten Acrowax C which melts at 275°F. Such coatings will resist acids and chemicals for a reasonable time.

#### ANODIC COATINGS

Aluminum, zinc, and cadmium are used for protection of steel because they are anodic electrically to the steel. No complete sealing of the coating is necessary. Aluminum and zinc are the two metals generally recommended for protection of iron and steel against atmosphere and water immersion. Coatings of zinc 0.001 in. thick provide excellent protection for small hardware items such as small nuts and screws. Aluminum coatings should not be sprayed less than 0.003 in. thick.

Aluminum requires a better surface preparation by grit blasting than zinc, and, therefore, zinc is used unless the properties of aluminum are desired.

Sprayed metal offers an excellent base for paint, owing to its porous structure. Paint may be added to sprayed-metal coatings either for appearance or as a means of providing more economical protection. The same life may be obtained from a thinner metallized coating which is painted as from a thicker coating unpainted.

Aluminum is a better base for paint than zinc, although zinc is satisfactory. Zinc chromate and iron oxide-zinc chromate paints in long oil varnish vehicles are excellent corrosion-inhibitive paints for aluminum and may also be used on zinc.

Vehicles made with Bakelite and glycerol phthalate resins are very satisfactory, and bituminous-base paints also give good results on both these metals. Paints with durable vehicles containing pigments such as aluminum, iron oxide, red lead, titanium oxide and zinc-zinc oxide have been found to give good wear on sprayed aluminum.

Very quick-drying types of paints or lacquers should be used only on thin coatings (0.005 in. thick or less) owing to the smaller extent of penetration into the pores.

Table 15-7 shows standard recommendations of coatings for salt atmosphere. Choices of the various combinations are largely based on the appearance requirements and/or the economic factors applicable to the particular job. From an appearance standpoint, one of the most desirable finishes is indicated in the table as "metallic appearance and bright finish" and is produced by painting aluminum with Bakelite varnish. This is a very desirable finish and will give a clean metal

TABLE 15-7. RECOMMENDED COATINGS FOR SALT ATMOSPHERES

The following recommendations are for large surfaces. Small objects which can be sprayed in barrels can generally be coated 0.001 to 0.002 in. thinner because coating thickness can be accurately controlled.

Requirement	For 15 Years Minimum Life	For 7 Years Minimum Life
Paint not required for appearance. No maintenance.	0.010-0.012" aluminum (for steel grit-blast job) or 0.012-0.015" zinc (for sand-blast job). No paint	0.006-0.008" aluminum (for sand- or grit-blast). No paint
Appearance not important. No maintenance.	0.007-0.010" aluminum (for sand- or grit-blast) plus one coat of paint *	0.004-0.006" aluminum (for sand- or grit-blast) plus one coat of paint *
Paint appearance desired. Repaint every 5 years.	0.004-0.006" aluminum (for sand- or grit-blast) plus one or more coats of paint *	Same as for 15 years minimum life
Metallic appearance and bright finish desired. Revarnish every 5 years.	0.004-0.006" aluminum (for sand- or grit-blast) plus one or more coats of Bakelite varnish or glycerol phthalate resin	Same as for 15 years minimum life

\* Paints recommended for aluminum or zinc: Zinc chromate and iron oxide-zinc chromate paints in long-oil varnish vehicles, vehicles made with Bakelite and glycerol phthalate resins and bituminous-base paints.

Additional paints recommended for aluminum only: Pigments such as aluminum, iron oxide, red lead, titanium oxide and zinc-zinc oxide with durable vehicles. Avoid quick-drying paints and lacquers except on very thin coatings.

TABLE 15-8. RECOMMENDED COATINGS FOR INDUSTRIAL ATMOSPHERES

The following recommendations are for large surfaces. Small objects which can be sprayed in barrels can generally be coated 0.001 to 0.002 in. thinner because coating thickness can be accurately controlled.

Requirement	For 20 Years Minimum Life	For 10 Years Minimum Life
Paint not required for appearance. No maintenance.	0.010-0.012" aluminum (for steel grit-blast job) or 0.012-0.015" zinc † (for sand-blast job). No paint	0.006-0.008" aluminum, 0.006-0.008" zinc. † No paint
Appearance not important. No maintenance.	0.007-0.010" aluminum or 0.007-0.010" zinc, † plus one coat of paint *	0.004-0.006" aluminum or 0.004-0.006" zinc, † plus one coat of paint *
Paint appearance desired. Repaint every 5 years.	0.004-0.006" aluminum or 0.004-0.006" zinc † plus one or more coats of paint *	Same as for 20 years minimum life
Metallic appearance and bright finish desired. Revarnish every 5 years.	0.004-0.006" aluminum plus one or more coats of Bakelite varnish or glycerol phthalate resin	Same as for 20 years minimum life

\* Paints recommended for aluminum or zinc: Zinc chromate and iron oxide-zinc chromate paints in long-oil varnish vehicles, vehicles made with Bakelite and glycerol phthalate resins and bituminous-base paints.

Additional paints recommended for aluminum only: Pigments such as aluminum, iron oxide, red lead, titanium oxide and zinc-zinc oxide with durable vehicles. Avoid quick-drying paints and lacquers except on very thin coatings.

† Use zinc where corners and edges are hard to reach or where it is difficult to get a good blast job; otherwise use aluminum, particularly where the coating is painted.



appearance. Maintenance is at a minimum, but the surface should be revarnished every 5 years.

TABLE 15-9. RECOMMENDED COATINGS FOR RURAL ATMOSPHERES

The following recommendations are for large surfaces. Small objects which can be sprayed in barrels can generally be coated 0.001 to 0.002 in. thinner because coating thickness can be accurately controlled.

Requirements	For 30 Years Minimum Life	For 20 Years Minimum Life	For 10 Years Minimum Life
Paint not required for appearance. No maintenance.	0.010-0.012" zinc. No paint	0.005-0.007" zinc. No paint	0.003-0.005" zinc. No paint
Paint appearance desired. Repaint every 5 years.	0.004-0.006" zinc plus one coat of paint *	Same as for 30 years min. life	Same as for 30 years min. life
Metallic appearance and bright finish desired. Revarnish every 5 years.	0.004-0.006" aluminum plus one or more coats of Bakelite varnish or glycerol phthalate resin	Same as for 30 years min. life	Same as for 30 years min. life

\* Paints recommended for aluminum or zinc: Zinc chromate and iron oxide-zinc chromate paints in long-oil varnish vehicles, vehicles made with Bakelite and glycerol phthalate resins and bituminous-base paints.

Additional paints recommended for aluminum only: Pigments such as aluminum, iron oxide, red lead, titanium oxide and zinc-zinc oxide with durable vehicles. Avoid quick-drying paints and lacquers except on very thin coatings.

Table 15-8 gives similar recommendations for heavy industrial atmospheres and Table 15-9 for rural atmospheres.

TABLE 15-10. RECOMMENDED COATINGS FOR IMMERSION IN COLD FRESH WATER

The following recommendations are for large surfaces. Small objects which can be sprayed in barrels can generally be coated 0.001 to 0.002 in. thinner because coating thickness can be accurately controlled.

Requirement	For 15 Years Minimum Life	For 7 Years Minimum Life
Paint not required for appearance. No maintenance.	0.012-0.015" zinc. No paint or 0.010-0.012" aluminum (steel grit only). No paint	0.006-0.008" zinc or 0.006-0.008" aluminum
Appearance not important. No maintenance.	0.008-0.010" zinc plus two coats paint * or 0.006-0.008" aluminum plus two coats of paint *	0.003-0.005" zinc plus two coats of paint * or 0.004-0.006" aluminum plus one coat of paint *

\* Paints recommended for aluminum or zinc: Zinc chromate and iron oxide-zinc chromate paints in long-oil varnish vehicles, vehicles made with Bakelite and glycerol phthalate resins and bituminous-base paints.

Additional paints recommended for aluminum only: Pigments such as aluminum, iron oxide, red lead, titanium oxide and zinc-zinc oxide with durable vehicles. Avoid quick-drying paints and lacquers except on very thin coatings.

Zinc and aluminum are both quite satisfactory for protecting steel when immersed in cold fresh water. Table 15-10 summarizes recom-

mendations for this service. Immersion conditions are usually more severe than atmospheric conditions, but in immersion there is the advantage that there is greater electrolytic protection to uncoated areas around seams, joints, and the like, particularly when zinc is used.

The problems involved in sea-water immersion are either corrosion or fouling with sea growth. Table 15-11 gives recommendations for various sea-water conditions. Pure zinc is a fair antifouling material if used unpainted. Sprayed coatings of aluminum offer very satisfactory corrosion resistance particularly when applied over a thin undercoat (0.0005-0.001 in.) of Sprasteel 10.

TABLE 15-11. RECOMMENDED COATINGS FOR IMMERSION IN SEA WATER

The following recommendations are for large surfaces. Small objects which can be sprayed in barrels can generally be coated 0.001 to 0.002 in. thinner because coating thickness can be accurately controlled.

Requirement	For 10 Years Minimum Life	For 5 Years Minimum Life
Paint not required for appearance. No maintenance.	0.010-0.012" aluminum or 0.010-0.012" zinc *	0.006-0.008" aluminum or 0.006-0.008" zinc *

\* Pure unpainted zinc is a fairly good antifouling coating. Unpainted aluminum fouls badly. Ships equipped with bronze propellers cannot be coated with zinc.

Where painting is to be done over sprayed metal, the best life will be obtained with high-quality paints and particularly those paints and resins recommended in the charts. It is quite safe, however, to use any commercial paints in any color directly on either aluminum or zinc, where particular colors are required for appearance. Using a primer such as zinc chromate will, of course, increase the life of the color coating.

Aluminum coatings on steel are generally recommended for immersion in hot fresh water, particularly hard water. There is considerable variation in the life of coatings, depending on the nature of the water. Generally, the aluminum stands up very well in hard water and in most soft waters. There are, however, some soft waters which reduce the life of aluminum coatings considerably.

Zinc is not satisfactory in hot water above 125°F.

Aluminum gives excellent protection to steel in distilled water, hot or cold. Zinc should not be used for distilled water.

## HEAT-CORROSION RESISTANCE

Several combinations of sprayed coatings of aluminum and of chromium-nickel alloys plus aluminum have been worked out, which

offer good protection to iron and steel subjected to the corrosive action of hot gases.

Sprayed aluminum is used for temperatures up to approximately 1600°F. The aluminum is applied about 0.005 in. thick and is then coated with a paint-type sealer. The articles are then heat-treated at a temperature of 1450°F and are usually wire-brushed after heat treatment. Sodium silicate has been used as the sealer in past years. A new sealer has been developed and is sold under the proprietary trade name of Metcoseal, which has proved more satisfactory for this purpose.

The processes involving the use of nickel-chromium alloys and aluminum are covered by U. S. patent 2,300,400 and are marketed under the proprietary trade name Metcolized as either Process 33 or Process 45.

Process 33 is satisfactory for temperatures up to 1600° to 1800°F for uses where sulfur gases are not present in substantial amounts.

Process 45 is satisfactory for temperatures up to about 2000°F and will withstand strong sulfur gases.

These heat-resistant sprayed-metal coatings are used quite extensively for such items as magnesium superheaters, aluminum melting pots, neutral salt pots, and furnace conveyors.

## Glass-Lined Steel Equipment

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In the manufacture of glass-lined steel equipment there is one marked difference which places it outside the general classification of a laminated material. This difference is due primarily to the fact that laminated raw material in various shapes and thicknesses is not used in the fabrication of glass-lined steel equipment. The equipment is completely fabricated from steel, and then the glass, in proper form, is applied to the entire interior surface, and fused to the steel by means of heat. The process of fusing the glass to the steel may be repeated by applying the same glass or any combination of glasses until a perfect coating over the entire interior surface is obtained.

### RAW MATERIALS

One of the most important base materials is the steel used in fabricating the equipment. In general, the types of steels used and the chemical composition and physical properties, are as follows:

*Class of Steel:* Hypoeutectoid.

*Types of Steels:* Rimmed, killed, and certain low-alloy carbon steels.

#### *Chemical Analysis:*

Carbon:	0.20% max.
Manganese:	0.50% max.
Phosphorus:	0.02% max.
Sulfur:	0.05% max.
Silicon:	0.05% max.

#### *Physical Properties:*

Proportional limit:	21,400 psi
Yield point:	34,000 psi
Tensile Strength:	55,000 psi
Elongation:	

In 2 in.:	40.0 per cent
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In 8 in.:	25.0 per cent
-----------	---------------

Reduction in area:	45.0 per cent
--------------------	---------------

All steel used for glass covering should be carefully inspected before fabrication for surface defects such as small blisters and slivers, and, if these are found to be excessive, the steel should be rejected for glass covering and used for other purposes. Freedom of defects on the steel surface is essential, and, if this factor is neglected, the result will be excessive rework and possible rejection of the unit. The raw materials used in producing glass for covering steel should be of the highest purity possible and subjected to frequent checks by the chemical laboratory.

Weighing, mixing, charging, smelting, pouring, drying, and milling are common knowledge, the details of which may be found in publications on the subject of the manufacture of glass or enamels.

#### FABRICATION OF STEEL UNITS

Steel in the form of rectangular plates covering a thickness range of  $\frac{3}{8}$  to 1 in., depending on pressure specification, is cut to size, edge-beveled, rolled, and tacked for welding. Steel circles, of varying diameters and thickness, are heated and shaped by means of hydraulic presses using forms to produce any standard shape and diameter or by spinning.

Openings and flanged connections specified for the heads are generally made before the heads are welded to the cylindrical portion of the unit. Flanged connections specified for the shell or cylindrical portion of the unit are made before the last head is welded on.

#### WELDING

All girth and longitudinal welds are made by means of automatic welding units employing alternating current. Manual shielded electric-arc welding is resorted to when it is impractical to apply the automatic electric-arc welding method.

All welding operators, manual or automatic, are qualified in accordance with the procedure as set forth in the ASME and ASME-API Codes for "Unfired Pressure Vessels." All welders are requalified every 6 months.

Electric-arc welding is a very important operation and must be performed with care. Good fits and attention to welding technique will practically eliminate defects appearing in the glass covering.

All welds should be checked by some quick method in order to reveal any serious hidden defects such as insufficient penetration, cracks, gas pockets, and slag inclusions. When such defects are revealed they should be cut out and these areas rewelded and rechecked.

After the welds have passed inspection, the interior surface of the unit is given a stress-relieving heat treatment. The unit then passes to the sand-blasting department where the interior surface is cleaned and subjected to a final inspection for steel surface defects.

On completion of the final steel inspection, the interior surface of the unit is given a thorough final sand blasting, cleaned and then passed to the glass application department where the finely ground glass, in slip form, is sprayed on the interior steel surface, dried, and then placed in a furnace wherein the unit is heated to a temperature at which the glass softens, smooths out, and fuses to the steel surface.

TABLE 16-1

Glass No.	Specific Gravity	Specific Heat	Modulus of Elasticity, psi	Coefficient of Linear Expansion *
27	2.60	0.208	10,447,000	0.00000984
42	2.52	0.201	10,472,000	0.00001014
42PF	2.55	0.213	10,468,000	0.00000991
24	2.52	0.201	10,472,000	0.00001014

\* Values cover a temperature range from room temperature to 400°C.

On completion of the first cover coat of the highly acid resisting glass, the entire interior surface is subjected to test by means of a high-frequency unit. This voltage test is for the purpose of detecting minute flaws in the glass coating. These minute defects, chiefly fine porosity, are eliminated by subsequent coats of glass until the high-voltage test reveals a perfect coating. The high-frequency test units used for this inspection work are checked prior to all tests by adjusting the spark to jump a 1-in. air gap.

Equipment passing the high-voltage test is then passed to the assembly department where the necessary accessories are attached, after which it is subjected to final tests and inspection prior to shipment.

The respective glasses used for glass-lined steel equipment are compounded and smelted under very careful temperature control. This procedure is similar to the operation of any glass tank furnace with the exception that the furnace is of smaller capacity.

Each batch of dry fritted glass is subjected to a fusion test and actual firing test on steel, in order to detect any marked deviation from standard values which are based on years of actual factory operations. Any batch of glass varying from the standard test values is rejected.

The next operation is the milling of the glass in both wet or slip form and dry milling. All millings are subjected to a screen test, and

TABLE 16-2. CHEMICAL DURABILITY PFAUDLER STANDARD GLASSES, ROOM TEMPERATURE, INCH PENETRATION PER YEAR

Acid Concentration, per cent by Weight	Number of Glass			
	27	42	42PF	24
<i>Hydrochloric Acid</i>				
2	0.00007512	0.00001803	0.00001184	0.00001140
5	0.00013476	0.00001918	0.00001977	0.00001145
10	0.00043004	0.00001752	0.00001681	0.00001555
20	0.00150210	0.00001826	0.00002813	0.00002135
36	0.00002188	0.00001964	0.00000820	0.00001314
<i>Sulfuric Acid</i>				
2	0.00006186	0.00000393	0.00000593	0.00000212
5	0.00017701	0.00002010	0.00001823	0.00001114
10	0.00037823	0.00000735	0.00000743	0.00000777
20	0.00030297	0.00001726	0.00001261	0.00001430
40	0.00029966	0.00001362	0.00000937	0.00001012
60	0.00002283	0.00001007	0.00000956	0.00001052
80	0.00000693	0.00001372	0.00001131	0.00001143
95	0.00001109	0.00001363	0.00001131	0.00001423
<i>Nitric Acid</i>				
2	0.00005040	0.00001350	0.00000822	0.00001033
5	0.00008967	0.00001240	0.00001001	0.00001042
10	0.00014166	0.00000921	0.00000965	0.00001126
20	0.00023504	0.00002680	0.00001851	0.00001932
40	0.00009604	0.00001347	0.00001589	0.00000919
60	0.00002205	0.00001857	0.00000983	0.00001141
72	0.00001121	0.00001269	0.00000975	0.00001427
<i>Phosphoric Acid</i>				
2	0.00001949	0.00000591	0.00000787	0.00000566
5	0.00002273	0.00000839	0.00000549	0.00000586
10	0.00001308	0.00000791	0.00000762	0.00000394
20	0.00003774	0.00001733	0.00001160	0.00000961
40	0.00005907	0.00001858	0.00001540	0.00001383
60	0.00005382	0.00001951	0.00001484	0.00001180
85	0.00000940	0.00001358	0.00000573	0.00000560
<i>Chromic Acid</i>				
2	0.00009587	0.00000527	0.00001424	0.00000371
5	0.00025467	0.00001682	0.00001617	0.00001138
10	0.00088845	0.00001992	0.00001914	0.00001776
20	0.00106990	0.00002122	0.00002459	0.00002857
40	0.00064825	0.00000577	0.00001410	0.00000956
60	0.00001584	0.00000944	0.00000177	0.00000976
<i>Formic Acid</i>				
2	0.00003292	0.00003370	0.00000923	0.00001147
5	0.00002956	0.00000539	0.00001299	0.00000605
10	0.00004728	0.00003787	0.00000946	0.00001365
20	0.00007034	0.00001095	0.00001311	0.00000576
40	0.00004215	0.00003125	0.00006550	0.00000765
60	0.00001243	0.00000377	0.00000357	0.00000580
80	0.00000179	0.00003312	0.00002366	0.00000374
86	0.00000538	0.00000904	0.00000892	0.00000973

TABLE 16-2. CHEMICAL DURABILITY, PFAUDLER STANDARD GLASSES, ROOM TEMPERATURE, INCH PENETRATION PER YEAR (*Continued*)

Acid Concentration, per cent by Weight	Number of Glass			
	27	42	42PF	24
<i>Acetic Acid</i>				
2	0.00000569	0.00000375	0.00000798	0.00000570
5	0.00001556	0.00000366	0.00000386	0.00000193
10	0.00000951	0.00000194	0.00000373	0.00000193
20	0.00000778	0.00000190	0.00000185	0.00000193
40	0.00000780	0.00000365	0.00003276	0.00000577
60	0.00000768	0.00000916	0.00003901	0.00000734
80	0.00000192	0.00000181	0.00000203	0.00000184
Glacial	0.00000362	0.00000740	0.00000379	0.00000578
Anhydride		0.00000383	0.00000191	0.00000407
<i>Lactic Acid</i>				
2	0.00004642	0.00000893	0.00002290	0.00001259
5	0.00005864	0.00001349	0.00002386	0.00002017
10	0.00009023	0.00001986	0.00002409	0.00002293
20	0.00011330	0.00002148	0.00004423	0.00002653
40	0.00013706	0.00003196	0.00004248	0.00003078
60	0.00006777	0.00001424	0.00001881	0.00002177
72	0.00001611	0.00000365	0.00001403	0.00001553
<i>Oxalic Acid</i>				
2	0.00063253	0.00003711	0.00001434	0.00000386
5	0.00071661	0.00004163	0.00001651	0.00000929
9	0.00056919	0.00003581	0.00002019	0.00000977
<i>Tartaric Acid</i>				
2	0.00005393	0.00001679	0.00001121	0.00001316
5	0.00004800	0.00001884	0.00001669	0.00002024
10	0.00006129	0.00001788	0.00001911	0.00002948
20	0.00007228	0.00003708	0.00002204	0.00002751
40	0.00010533	0.00005692	0.00004298	0.00004259
56	0.00020487	0.00006764	0.00007524	0.00006376
<i>Citric Acid</i>				
2	0.00015360	0.00000747	0.00000177	
5	0.00026199	0.00001749	0.00000708	0.00000393
10	0.00004486	0.00002055	0.00001777	0.00000931
20	0.00004454	0.00001398	0.00001734	0.00001320
40	0.00007261	0.00003145	0.00005733	0.00002038
66	0.00007729	0.00002849	0.00003149	0.00002903
<i>Tannic Acid</i>				
2	0.00002347	0.00000560	0.00000522	0.00000382
5	0.00002115	0.00000524	0.00000560	0.00000381
10	0.00001558	0.00000367	0.00000358	0.00000385



all wet millings are then checked for mobility and fineness distribution, prior to delivery to the glass covering department.

Some of the important properties of the respective glasses used for lining steel equipment are as shown in Table 16-1.

TABLE 16-3. CHEMICAL DURABILITY, PFAUDLER STANDARD GLASSES,  
INCH PENETRATION PER YEAR

Acid Concentration, per cent by Weight	Temperature—Boiling Number of Glass	
	42	42PF
<i>Hydrochloric Acid</i>		
5	0.00051273	0.00050210
10	0.00030603	0.00050750
20	0.00003287	0.00011230
<i>Sulfuric Acid</i>		
5	0.00058253	0.00067035
20	0.00147790	0.00151690
40	0.00014056	0.00018708
80	No Action	No Action
<i>Nitric Acid</i>		
5	0.00028260	0.00022520
20	0.00120150	0.00113700
40	0.00000793	0.00011940
69	0.00008590	0.00014615
<i>Phosphoric Acid</i>		
5	0.00032920	0.00086600
20	0.00078300	0.00105830
40	0.00136700	0.00157170
85	0.01618500	0.02769500
<i>Acetic Acid</i>		
5	0.00025977	0.00045951
40	0.00009275	0.00024006
99.5	0.00004128	0.00008258

Another very important property of glass used for lining steel equipment is its chemical durability. In order to obtain data relative to the attack of some of the more commonly used inorganic and organic acids, complete immersion tests were conducted at both room temperature and boiling temperatures of the various concentrations of acids used. The results are given in Tables 16-2 and 16-3, expressed in inch penetration per year.

The values given for the chemical durability of the glasses at room temperature are based on a test period of 6 months, whereas the elevated temperature tests were conducted for 30 days of continuous boiling.

The "inch penetration per year" values must be regarded as relative because in cases of rather vigorous action it is quite difficult to remove all corrosion products from the test piece prior to determining loss in weight. The data given are of value in estimating the probable service life of the glass under any condition simulating the conditions of the respective tests.

TABLE 16-4. CHEMICAL DURABILITY, PFAUDLER STANDARD GLASSES, ROOM TEMPERATURE, INCH PENETRATION PER YEAR

pH Value	Hydrogen-Ion Scale Number of Glass			
	27	42	42PF	24
0	0.00024062	0.00003390	0.00003992	0.00002706
1	0.00010202	0.00002979	0.00002576	0.00002928
2	0.00002120	0.00001618	0.00001775	0.00003349
3	0.00002811	0.00002309	0.00001749	0.00003085
4	0.00002757	0.00001677	0.00001642	0.00001397
5	0.00003246	0.00001080	0.00001205	0.00002268
6	0.00006134	0.00002997	0.00000908	0.00003263
7	0.00010871	0.00002812	0.00004166	0.00003662
8	0.00011959	0.00001791	0.00001552	0.00002805
9	0.00010029	0.00002876	0.00001815	0.00003484
10	0.00009769	0.00003404	0.00004754	0.00007135
11	0.00014456	0.00007366	0.00006533	0.00006139
12	0.00017609	0.00009937	0.00001705	0.00011148
13	0.00029433	0.00025830	0.00037434	0.00022166
14	0.00035018	0.00032393	0.00032521	0.00022161

It must be pointed out that the estimated service life of glass-lined steel equipment is not solely a function of the chemical durability but may be greatly influenced by uncontrollable variables such as areas of subaverage thickness, abrasion, imperfections in the steel shell or the glass, or mechanical injury.

Data are also given in Table 16-4 covering the hydrogen-ion range, pH 0 to pH 14, at room temperature, of the chemical durability of Pfaudler Standard Glasses. It may be noted that the over-all corrosion resistance of the respective glasses is very satisfactory, but, as the operating temperature is increased above room temperature, the chemical durability decreases very rapidly beyond pH 10 with the re-



FIG. 16-1. 750-gal Type LL. Reaction units for synthetic vitamins.



FIG. 16-2. Jacketed Glass-Lined Steel Units for Processing Liver Extract.

sult that the service life of the glass-lined steel equipment may be unsatisfactory.

In calculating the probable life of the glasses applied to steel equipment, it is suggested that the minimum average thickness of the glass be taken as 36 mils. This suggested thickness value does not include



FIG. 16-3. Glass-Lined Steel Equipment for Distillation of Alcohol.

what is commonly called the ground coat of glass. In actual units this suggested glass thickness value of 36 mils may be exceeded; yet experience has supported its use in all service life calculations based on corrosion tests.

For heat-transfer calculations involving glass-lined steel equipment, the value of 99 Btu per square foot per hour per inch per degree Fahrenheit may be used. This value is based on the following:

Glass: 6.5 Btu/sq ft/hr/in./°F

Steel: 312 Btu/sq ft/hr/in./°F

Average thickness of glass (including ground coat): 0.045 in.

Regarding hardness, abrasion resistance and thermal endurance, reliable data are not available, owing to the fact that satisfactory tests covering these properties have not yet been developed.

Glass-lined steel equipment (Figs. 16-1, 16-2, and 16-3) is used in practically all industries, wherever corrosive conditions are involved. In the chemical industry glass-lined steel equipment is successfully used for processes involving nitration, halogenation (excepting compounds containing fluorine), sulfonation, oxidation, polymerization, esterification, and the Friedel and Crafts reaction.

Glass-lined steel equipment should not be used for handling the fixed alkalis, hydrofluoric acid or fluorides, and high concentrations of phosphoric acid at elevated temperatures.

## Composite-Glass Structures

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### PRINCIPLE OF CONSTRUCTION

Generally, the construction of glass composites or laminates consists in bonding together two or more sheets or plates of glass with one or more layers of plastic or nonbrittle material to produce a composite structure.

Modifications of the general construction are found in combining sheets or plates of glass with sheets of dissimilar materials, such as wood, fabrics, cement, and ceramic bodies, through the medium of proper adhesives or bonding agents interposed between and adjacent to the different layers forming the composite.

Further modifications consist of plates or sheets of glass enclosing layers of air for insulating purposes. In this construction, the glass plates are united or bonded at the margin, thus forming an air cell of predetermined thickness.

### GLASS COMPONENTS

#### COMPOSITION, CLASSIFICATION, AND PROPERTIES

Although it is recognized that the composition of glass can vary widely, depending on the particular application for which it is designed, the types of glass most commonly used for laminating purposes are referred to generically as "flat glass," having a soda-lime-silica-base composition. Therefore, the plates or sheets of glass serving as an integral part of any glass composite in this book, unless specifically mentioned, refer to flat-glass products of the soda-lime-silica type.

Flat glass used for composite structures or laminates may be broadly classified as transparent, translucent, and opaque glasses.

**1. Transparent Glasses.** Transparent glasses, used extensively for glazing purposes, include:

(a) *Sheet or Window Glass.* Sheet or window glass is characterized by its fire-finish surface, formed or produced as the sheet is drawn from the molten pool of glass.

(b) *Plate Glass.* Plate glass is characterized by a machined surface, produced by mechanically grinding and polishing the surfaces of the plate-glass blanks after forming. The advantages of plate glass over sheet or window glass that justify the grinding and polishing operations are not necessarily the improved quality of finish, but rather flatness and parallelism of the glass surfaces, which serve to minimize distortion of objects viewed through it.

(c) *Colored Glasses.* Colored, transparent glasses, produced by adding small percentages of certain metal compounds to plate- and sheet-glass batches, find application for light filtering and decorative purposes.

**2. Translucent Glasses.** Translucent glasses, widely used for glazing purposes, include:

(a) *Figured Glasses.* The translucent characteristics of figured glass are due to light scattering, caused by the roughened or figured pattern placed on the glass surface during the process of manufacture.

(b) *Opal Glass.* The translucent characteristics of opal glass are due to light scattering; however, the light scattering is caused by opaque particles dispersed in the glass matrix, rather than surface effect as in the case of figured glasses.

**3. Opaque or Structural Glasses.** Opaque structural glasses, as manufactured in the United States and sold under the trade names of Carrara and Vitrolite, are available in various colors ranging from black to nearly white and can be furnished with ground and polished surfaces, similar to plate glass, or with the natural fire-finish surface.

#### PHYSICAL AND CHEMICAL CHARACTERISTICS

Following are some of the more important physical and chemical properties of the flat glasses having a soda-lime-silica-base composition:

Specific gravity (70°F)	2.45 to 2.60
Weight per sq ft per in. thickness	12.7 to 13.5 lb
Tensile ultimate (modulus of rupture)	6000 psi cross section
Modulus of elasticity (Young's modulus)	10,000,000 psi

**Hardness:**

(a) Mohs's scale (diamond = 10; talc = 1)	5.5 to 6.5
(b) Knoop (Tukon tester)	310 to 480
Softening point	1300 to 1350°F
Thermal conductivity ( <i>k</i> ) (0°–120°F)	4.0 Btu per sq ft per hr per in. thick- ness per °F
Specific heat (32° to 212°F)	0.20
Coefficient of linear expansion (temp. range 32° to 555°F)	4.45 to 6.0 × 10 <sup>-6</sup> per °F

All soda-lime-silica-base glasses are readily attacked by hydrofluoric acid but are generally resistant to most other acids at normal temperatures.

Transparent ordinary plate and sheet glasses have a total visible white-light transmission of 88 to 92 per cent in thicknesses up to ¼ in.

**HEAT-STRENGTHENED GLASS**

The strength characteristics of soda-lime-silica glass can be increased materially by subjecting the glass to a special heat-treating operation, which places the outside layers in a high state of compression.

TABLE 17-1. STRENGTH TESTS (REGULAR ¼ IN. PLATE GLASS)  
Temperature of Test Specimens: 75°F

Pressure Loading: 5 psi per min

Glass	Method of Glazing	Average Breaking Pressure, psi Glass Size (Free Opening)		
		12" x 12"	18" x 18"	24" x 24"
¼" plate regular	Clamped at margin with gasket	14	7	4.5

TABLE 17-2. STRENGTH TESTS (HEAT-STRENGTHENED ¼ IN. PLATE GLASS)  
Temperature of Test Specimens: 75°F

Pressure Loading: 5 psi per min

Glass	Method of Glazing	Average Breaking Pressure, psi Glass Size (Free Opening)		
		12" x 12"	18" x 18"	24" x 24"
¼" plate heat-strengthened	Clamped at margin with gasket	60	30	15

Such a heat-treating operation serves to increase the strength of glass having a thickness of ¼ in. and greater approximately three to five times that of ordinary annealed glass of the same thickness.



The results of strength tests conducted on regular or annealed and heat-strengthened plate glass, 12 in. by 12 in., 18 in. by 18 in., and 24 in. by 24 in. (free opening) and having a nominal thickness of  $\frac{1}{8}$  in., are recorded in Tables 17-1 and 17-2. The breaking pressures recorded are the average of at least six specimens.

TABLE 17-3. BENDING TESTS (MODULUS OF RUPTURE) REGULAR OR ANNEALED  $\frac{1}{8}$ -IN. PLATE GLASS

Temperature, °F	Span, in.	Width of Glass Specimens, in.	Glass Thick- ness, in.	Deflec- tion, in.	Break- ing Load, lb	Modulus of Rupture, psi
-73	10	3.85	0.132	0.165	90	20,130
-73	10	3.80	0.130	0.154	90	16,800
-73	10	3.81	0.131	0.120	76	17,440
-73	10	3.85	0.128	0.121	60	14,940
-73	10	3.83	0.128	0.118	62	14,820
					Average	16,800
125	10	3.84	0.127	0.068	30	7,785
125	10	3.82	0.125	.....	24	6,246
125	10	3.79	0.124	0.045	20.2	5,198
125	10	3.84	0.126	0.074	34	8,363
					Average	6,898

TABLE 17-4. BENDING TESTS (MODULUS OF RUPTURE) HEAT-STRENGTHENED  $\frac{1}{8}$ -IN. PLATE GLASS

Temperature, °F	Span, in.	Width of Glass Specimens, in.	Glass Thick- ness, in.	Deflec- tion, in.	Break- ing Load, lb	Modulus of Rupture, psi
-76	10	3.82	0.131	0.271	137	31,240
-76	10	3.82	0.130	0.315	195	45,310
-76	10	3.80	0.119	0.174	72	26,050
-76	10	3.81	0.125	0.269	160	56,340
-76	10	3.78	0.127	0.242	115	40,490
					Average	39,900
125	10	3.78	0.118	0.252	98	35,800
125	10	3.81	0.129	0.255	115	39,860
125	10	3.82	0.134	0.197	100	33,920
125	10	3.78	0.127	0.188	82	22,940
125	10	3.81	0.130	0.140	94	21,900
					Average	30,900

#### VARIATION OF STRENGTH OF GLASS WITH TEMPERATURE

Results of bending tests conducted on  $\frac{1}{8}$ -in. annealed and heat-strengthened glass at 125° and -75°F are recorded in Tables 17-3 and

17-4, showing distance between supports, width and thickness of glass specimens, breaking load in pounds, deflection at time of rupture, and modulus of rupture in pounds per square inch.

From the results recorded in Tables 17-3 and 17-4, it may be seen that the modulus of rupture for annealed  $\frac{1}{8}$ -in. plate glass increases over 100 per cent as the temperature decreases from 125° to -75°F. For heat-strengthened glass the resistance to bending is not so marked, showing an increase in strength of approximately 25 per cent over the same temperature range.

### INTERLAYER COMPONENTS

Adherent materials varying from very thin coats or layers to sheets of considerable thickness and capable of bonding glass to glass or glass to dissimilar materials to form composite structures may be classified for the purpose of simplicity as:

1. *Plastics*, where transparency is a prerequisite.
2. *Mastics*, where transparency is of no importance.

### PLASTICS

During the past two decades, various types of transparent plastics have been used for making glass-plastic laminates, including pyroxylin plastic, cellulose acetate plastic, and plasticized methacrylate resin. At the present time, however, these plastics have been almost entirely supplanted in the United States by a plasticized vinyl resin. More specifically, the vinyl resin is polyvinyl butyral resin plasticized with the proper amount and kind of plasticizer. The three commonly used plasticizers are: 3-GH (triethylene glycol dihexoate), J-24 (triethylene glycol, esterified with certain fatty acids derived from cocoanut oil), and dibutyl sebacate, in the approximate amounts of 20 to 30 per cent. The different percentages of plasticizer vary with the type and also the application to be made of the finished glass composite.

### MASTICS

The term "mastics" as used commercially embraces a great many materials having wide application in industry. They may be defined as pasty adherent materials used for coating, cementing, and caulking purposes. The more common mastics usually fall in the classification of asphaltic and putty types; however, during the Second World War certain synthetic-rubber mastics were developed which served very important applications for bonding glass to other materials.

### HISTORY

The art of combining laminas of glass and other materials to form composite structures was recognized and practiced as early as 1885, when Arthur Thomas Fullicks<sup>1</sup> of England obtained different coloring effects into one composite pane of glass by carefully arranging pieces of differently colored glass in pattern form and cementing this pattern with suitable adhesives between two plates or sheets of clear glass.

As far as public records reveal, the idea of reinforcing glass for safety purposes by laminating with plastics was first conceived by an Englishman, John Crewe Wood,<sup>2</sup> who obtained British and United States patents in 1905 and 1906, respectively, describing a method for the manufacture of safety glass by cementing with Canada balsam a sheet of transparent celluloid plastic between two panes of glass. Wood's venture was without success, presumably because of the high cost of materials, poor quality of product, and small demand.

In 1910 a Frenchman named Benedictus<sup>3</sup> obtained French and British patents for the manufacture of laminated safety glass, employing the same general principle as Wood, except that he proposed gelatin and other materials, instead of Canada balsam, for adhering the glass-plastic layers. Benedictus named his product "Triplex," and the French firm that manufactured his article was called La Société du Verre Triplex. The latter part of 1912, the Triplex Safety Glass Company, Ltd., purchased patent rights from the French company and commenced the manufacture of laminated safety glass at Willesden, England, in the middle of 1913.

It was not, however, until 1914, at the time of World War I, that any real progress was made. The demand for laminated glass for goggle lenses, gas masks, and windshields for motor vehicles and aircraft served to establish its manufacture as an industry during World War I.

Although the merits of laminated safety glass had been established, for some years following the war little progress was made to improve the quality and stability of the celluloid plastic (the only plastic commercially available for the purpose) for uniting glass plates, resulting in the industry remaining at a standstill, if not in the waning class.

The trend in the motorcar industry from open- to closed-model cars in 1925 presaged the increased use of glass for automobile glazings. The glass and plastic manufacturers, realizing the worth-while contribution in the way of increased safety that a well-made safety glass would afford the motoring public, made substantial investments in re-

search and manufacturing facilities which in a few years resulted in a much improved safety-glass product from the standpoint of clarity and stability.

Milestones in the safety-glass industry resulting from organized research were:

1. The development in 1931 of the autoclave to replace platen presses for uniting the glass-plastic layers.

2. The development in 1931 of roll equipment for applying adhesives continuously.

3. The development in 1932 of the more stable cellulose acetate plastic and adhesives for bonding the glass-plastic layers.

4. The development in 1932 of extruding equipment for producing plastic sheeting in a continuous manner.

5. The development in 1937 of a polyvinyl acetal resin plastic that can be bonded directly to glass by the application of heat and pressure, thereby making available commercially a superior safety glass from the standpoint of resistance to impact, and weathering, as compared to plastic laminations previously produced. This plastic is widely used at the present time for safety-glass manufacture.

#### **TRANSPARENT GLASS-PLASTIC LAMINATES**

The problems involved in the manufacture of transparent laminated glass are probably different in the main from those met with in most industries because of the difficulties in satisfactorily bonding unlike materials together to give a clear transparent composite structure, having the desired characteristics of greater resistance to shock and penetration, when used under the conditions for which it was designed.

Transparent glass laminates include:

1. Laminated safety glass for glazing motor vehicles, railway passenger and Pullman cars, and all other applications where the breaking of glass constitutes a hazard.

2. Aircraft safety glass.

3. Bullet-resisting glass.

4. Laminated glass filters.

#### **LAMINATED SAFETY GLASS**

Laminated safety glass usually consists of two lights of sheet or plate glass having a nominal thickness of 0.095 to 0.115 in. bonded or united together with an interposed layer of vinyl plastic (polyvinyl

butyral resin plasticized with 28 to 30 per cent plasticizer) 0.015 in. thick. However, glass of lesser or greater thickness than the range mentioned can and is used for laminated safety glass for special applications. Likewise, plastic thicker than 0.015 in. is used as the non-brittle layer in the laminates, when greater resistance to impact is desired.

#### MANUFACTURING

Briefly, the process for the manufacture of laminated safety glass involves the assembly of a clean dry sheet of plastic between two lights of clean dry glass, subjecting the resulting glass-plastic assembly or sandwich to a preliminary heating and pressing action, to exclude non-condensable gases, such as air, and to provide sufficient adhesion between the glass-plastic layers to permit handling as a composite. The partially bonded structures are then placed in an autoclave where the glass-plastic layers are firmly united by the further application of heat and pressure.

#### STEPS IN MANUFACTURE

**Plastic Processing.** The vinyl plastic widely used for safety-glass laminates, as supplied by the plastic manufacturers is quite hygroscopic, absorbing as high as 4 per cent moisture when at equilibrium in an atmosphere of 100 per cent relative humidity. Because of the tacky characteristics of the plastic sheeting, its surfaces are coated by dusting with soda (sodium bicarbonate) to permit shipment in rolls and to facilitate handling, such as, drying, cutting, and washing, in the laminator's plant.

**Drying.** Important to good dependable adhesion between the glass-plastic laminas, as well as good stability of the finished product, is low moisture content of the vinyl plastic at the time of laminating. Although vinyl plastics are more or less water-sensitive from the standpoint of adhesion to glass, depending on the plasticizer used, the practice of drying and handling the vinyl plastic to hold the moisture content to 0.5 per cent maximum at the time of assembly between glass sheets, has proved satisfactory for the three plasticizers mentioned previously.

The moisture content of the plastic sheeting is reduced to 0.2 per cent or less by carrying the sheet on roll mechanism through suitable drying ovens at temperatures ranging from 150° to 160°F. The time for drying will vary from 6 to 10 min., depending on the moisture content of the plastic as received, and also on the water-carrying capacity of the

air used in the drying oven. The plastic as discharged from the oven should be maintained in a conditioned atmosphere having a relative humidity of 20 per cent maximum.

**Cutting.** Although laminated safety glass can be cut to pattern from stock sheets, it is more economical to fabricate safety glass to exact size. Accordingly, the plastic after drying is cut to the exact size and shape of the finished laminated safety glass. This operation can be performed with hand tools. However, the usual practice is to convey the plastic sheeting through die-blanking machines for cutting to the desired pattern size.

**Washing.** Before assembly between glass plates, it is necessary to remove all traces of the soda which remained on the sheet during the drying and cutting operations. This is accomplished by passing the plastic through special washing machines where an application of hot water, followed by cold water, dissolves and flushes the soda from the plastic surfaces.

By controlling the water temperature and time of contact with the plastic sheet, the water pickup by the plastic can be held to approximately 0.1 per cent. Following the washing operation the plastic is ready for assembly between lights of glass preliminary to lamination.

TABLE 17-5. WATER CONTENT OF VINYL PLASTIC VERSUS  
GLASS-PLASTIC ADHESION

% Moisture Content of Plastic at Time of Lamination	Adhesion
0 to 0.5	Excellent
0.5 to 1.0	Good
1.0 to 2.0	Fair
2.0 to 4.0	Poor to none

The importance of moisture control of the polyvinyl butyral resin plastic when used for bonding to glass is illustrated in Table 17-5, which shows the kind of adhesion obtained on laminated safety glass when the vinyl plastic interlayer contained different amounts of water at the time of lamination.

## GLASS PROCESSING

**Cutting.** Lights of plate or sheet glass of the desired thickness are first cut to the proper size or pattern of the finished laminated glass and stacked in pairs on glass bucks.

**Washing.** The pattern-size glass is usually washed mechanically by feeding the flat glass in pairs through a horizontal washing machine.

The glass coming from the washing machine proper is rinsed and dried by passing through squeegee and wiping rolls and thence conveyed to the assembly room.

**Assembly.** In the assembly room, the plastic sheet is sandwiched between pairs of glass of the same pattern size and then conveyed to the prepressing machine, where the glass assembly is subjected to heat and slight roll pressure to exclude noncondensable gases and effect a preliminary bonding.

**Final Pressing.** Coming from the prepressing machine, where the continuous line operation terminates, the partially bonded assemblies are stacked in suitable racks, which are transferred to large autoclaves, where the final bonding is consummated by the application of pressures ranging from 200 to 250 psi and temperatures ranging from 240° to 300°F. The holding time at the maximum temperature and pressure for ordinary  $\frac{1}{4}$ -in. safety glass varies from 6 to 10 min.

The composite or laminate coming from the autoclave is washed, edge-finished to specifications, inspected, and boxed for shipment.

#### PHYSICAL PROPERTIES

Although many of the physical properties of  $\frac{1}{4}$  in. laminated safety glass, such as the index of refraction, light transmission, and surface hardness, are for all practical purposes, the same as the glass components used for making the composite structure, the modulus of rupture is lowered appreciably by the presence of the nonrigid plastic interlayer.

The results of pressure tests conducted on  $\frac{1}{4}$ -in. regular plate and laminated safety plate glass in sizes 12 in. by 12 in.; 18 in. by 18 in. and 24 in. by 24 in. recorded in Table 17-6 are the average of ten specimens and will serve to illustrate the reduction in strength due to the plastic interlayer.

TABLE 17-6. PRESSURE TESTS:  $\frac{1}{4}$ -IN. PLATE AND  $\frac{1}{4}$ -IN. SAFETY PLATE GLASS

Temperature of Test Specimens: 75°F Pressure Loading: 5 psi per min		Average Breaking Pressure, psi Glass Size (Free Opening)		
Glass Specimen	Method of Glazing	12" x 12"	18" x 18"	24" x 24"
$\frac{1}{4}$ " plate regular	Clamped with gaskets at margin	14	7	4.5
$\frac{1}{4}$ " safety plate ( $\frac{3}{16}$ " glass, 0.015 plastic, $\frac{1}{16}$ " glass	Clamped with gaskets at margin	11	6	3.5

## RESISTANCE TO IMPACT

The safety features of glass-plastic laminates depend quite largely on the adherent plastic layer to hold the composite together and thereby reduce the hazard of flying glass when the lamination is cracked or broken. It, therefore, follows that the resistance to impact and, therefore, the safety feature of laminated safety glass will depend on the plastic thickness used in the lamination, the glass components, and the temperature at the time of impact since the vinyl plastic used is a thermoplastic.

The results of impact tests conducted at 0°, 75°, and 120°F, with ½- and 2-lb steel spheres, on 12-in.-by-12-in. specimens of ¼-in. laminated safety glass, made with annealed and heat-strengthened ⅞-in. plate glass and vinyl plastic interlayers 0.015, 0.030, and 0.045 in. thick are recorded in Table 17-7.

TABLE 17-7. SUMMARY OF IMPACT TESTS ON LAMINATED SAFETY GLASS MADE WITH VINYL PLASTIC CONTAINING 28% DIBUTYL SEBACATE

Glass Components Used	Plastic Thick- ness, in.	Weight of Steel Ball, lb	Critical Distance, ft		
			0°F	75°F	120°F
⅞" plate	0.015	½	18	Greater than 33½	20
⅞" heat-strength- ened plate	0.015	½	22	Greater than 33½	27
⅞" plate	0.015	2	2¾	5¼	4¼
⅞" heat-strength- ened plate	0.015	2	5½	8	7
⅞" plate	0.030	2	7½	22	11
⅞" heat-strength- ened plate	0.030	2	10	33	15
⅞" plate	0.045	2	12	Greater than 33	33
⅞" heat-strength- ened plate	0.045	2	21	Greater than 33	33

The "critical distance" recorded in Table 17-7 resulted from testing at least 20 specimens and is that distance from which the steel sphere was allowed to fall from rest to produce failure of 50 per cent of the specimens tested. Specimens were classified as failures when a hole or continuous shear in the plastic interlayer exceeded 1½ in., even though the impacting sphere failed to penetrate the lamination completely.



Similar impact tests conducted on 12-in.-by-12-in. specimens of regular  $\frac{1}{4}$ -in. plate glass (annealed) with a  $\frac{1}{2}$ -lb steel sphere show the plate glass to have a critical distance of about 2 ft over the temperature range of 0° to 120°F.

#### TEMPERATURE STABILITY

To meet heat-stability requirements as specified in the American Standards Association Safety Code Z-26.1, laminated safety glass specimens, 12 in. by 12 in. in size, are required to withstand immersion in boiling water for a period of 2 hr without showing noticeable discoloration or bubble formation in the lamination.

Although vinyl plastic properly made and laminated will withstand the temperature of boiling water for short periods of time without showing apparent change, sustained temperatures much above 150°F will adversely affect the plastic interlayer, thereby decreasing its usefulness as a safety-glass product.

#### AIRCRAFT SAFETY GLASS

Although the general principle of laminating glass and plastic for automobile and aircraft glazings is the same, the functional requirements of safety glass for the modern aircraft differ widely from those used for glazing motor vehicles operating on land highways. Greater resistance to impact and pressure loads are required of aircraft safety glass. Also for streamlining purposes curved sections and different methods for glazing or mounting in the aircraft are necessary to afford flush joints that will be weather- and pressure-tight.

#### CONSTRUCTION

The strength requirements for aircraft glazings and, therefore, their construction will vary widely with the type, design, and performance specifications of the aircraft. For example, trainer planes and smaller aircraft function very satisfactorily with laminated safety glass as used for glazing automobiles; however, bombers, stratoliners and the modern aircraft in use by our Armed Forces operating under conditions of high speed, high elevations, or rapid change in elevation, require structural performance of the safety-glass glazings. To meet these severe requirements, aircraft safety glass is usually made with heat-strengthened glass united with vinyl plastic four to ten times the thickness used for automobile safety glass.

## EDGE CONSTRUCTION

Important to the proper functioning of aircraft glazings is the method of mounting the laminated structure in the plane openings. Using plastic of substantial thickness and allowing it to extend marginally beyond the edge of the glass plates affords means for glazing the safety-glass laminate by bolting or clamping through the extended plastic layer. Modification of this type of edge construction consists in re-

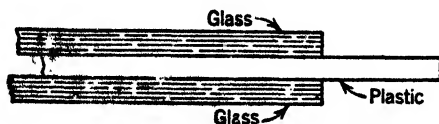


FIG. 17-1. Extended Plastic Edge.

inforcing the extended plastic flange by the insertion of a flexible metal collar inwardly  $\frac{1}{4}$  to  $\frac{3}{8}$  in. from the edge of the glass. The metal collar is laminated in the approximate center of the plastic flange and serves to reduce the extensibility of the plastic flange under load due to plastic flow.

The mountings just described afford flexibility that will minimize the strain in the glass structure due to the twisting or warping of the plane and also serve to compensate for the dimensional tolerances necessary in the manufacture of glass and plane openings. Also, since stream-

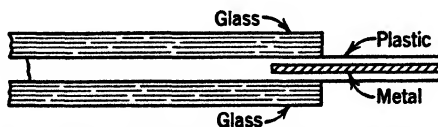


FIG. 17-2. Extended Plastic Edge Reinforced with Metal.

lining of aircraft generally requires curved-glass sections, particularly for pressurized cabins, the extended-plastic mountings serve to carry a portion of the pressure load in tension.

The two types of mountings, extended plastic and the metal-reinforced extended plastic, are shown in Figs. 17-1 and 17-2.

## PHYSICAL CHARACTERISTICS OF AIRCRAFT SAFETY GLASS

## Impact Resistance

The resistance of glass-plastic laminates to impacting objects will, of course, depend on the number and thickness of glass-plastic layers

used to make the composite. In times of war, aircraft glazings are the target for all types and kinds of impacts, including the steel dart used in armor-piercing ammunition, shrapnel, gun blast and birds in flight. During peacetime, however, perhaps the greatest impact hazard confronting air-carrier aircraft is that of collision with migratory birds, such as wild ducks and geese in flight. Therefore, to guard against such hazards, aircraft windshields must be constructed to resist the impacts of wild fowl weighing as much as 12 lb, at speeds equal to or even greater than the cruising speed of the aircraft.

The Civil Aeronautics Administration <sup>4</sup> has, with the co-operation of the glass and plastic manufacturers, done considerable research on this problem, and their results indicate that double-glazed windshields comprising ¼-in. laminated safety glass as the outboard light and laminated heat-strengthened glass with ⅜-in.-thick vinyl plastic as the inboard light will resist the impact of a 14-lb bird carcass at a velocity of approximately 200 mph.

### Strength in Tension of Plastic and Plastic-Reinforced Edges for Mounting

The results of tensional loading of the extended-plastic and the metal-reinforced extended-plastic edges for mounting aircraft safety glass made with ⅛-in.-thick vinyl plastic interlayer (containing 20 per cent dibutyl sebacate plasticizer) are given in Table 17-8. As the results in Table 17-8 show, the metal reinforcing materially reduces the extensibility of the edge mounting under load.

TABLE 17-8. TENSIONAL LOADING OF AIRCRAFT SAFETY GLASS AT 75°F

Type of Edge Construction	Kind and Thickness of Metal Reinforcing	Load in lb per linear in., Edge Support	Elongation under Load, in.	Remarks
Extended plastic ⅛" thick	Plastic only	9.5	1½	Plastic flowed
Extended plastic ⅛" thick, reinforced with continuous metal collar	Soft aluminum 0.025" thick	160	⅛	Aluminum frame sheared

### Pressure Loading

The results of pressure-loading glass-plastic laminations of aircraft construction and having the extended-plastic and metal-reinforced

# Physical Characteristics of Aircraft Safety Glass 597

extended-plastic edges for glazing are recorded in Tables 17-9, 17-10, and 17-11. The composite structures were made by laminating flat plates of heat-strengthened glass, with  $\frac{1}{8}$ -in.-thick vinyl plastic inter-layer (containing 20 per cent of dibutyl sebacate plasticizer).

TABLE 17-9. PRESSURE TESTS

Temperature of Test Specimen: 75°F

Rate of Pressure Loading: 1 psi per 5 min

Glass-Plastic Construction	Type of Edge Mounting	Glass Size (Free Opening) Average Breaking Pressure, psi		
		12" x 12"	18" x 18"	24" x 24"
$\frac{1}{8}$ " glass	Extended plastic	13	9	7
$\frac{1}{8}$ " plastic	Extended plastic,			
$\frac{1}{8}$ " glass	metal-reinforced	19	12	8
$\frac{1}{8}$ " glass	Extended plastic	17	11	9
$\frac{1}{8}$ " plastic	Extended plastic,			
$\frac{3}{16}$ " glass	metal-reinforced	31	22	12

If the breaking pressures recorded in Tables 17-9 and 17-10 are compared, it becomes apparent that the type of edge construction used for glazing or mounting aircraft safety glass is an influencing factor in predicting the pressure load that glass-plastic laminates of this construction will safely carry.

TABLE 17-10. PRESSURE TESTS

Temperature of Test Specimens: 75°F

Rate of Pressure Loading: 5 psi per min

Glass-Plastic Combination	Type of Edge Mounting	Glass Size (Free Opening) Average Breaking Pressure, psi		
		12" x 12"	18" x 18"	24" x 24"
$\frac{1}{8}$ " glass	Extended plastic	23	15	10
$\frac{1}{8}$ " plastic	Extended plastic,			
$\frac{1}{8}$ " glass	metal-reinforced	27	15	10
$\frac{1}{8}$ " glass	Extended plastic	33	20	15
$\frac{1}{8}$ " plastic	Extended plastic,			
$\frac{3}{16}$ " glass	metal-reinforced	44	21	15

The lower breaking pressures attained with the extended-plastic edge compared with those of similar specimens having the metal-reinforced plastic edge are attributable to greater plastic flow of the former. Also the lower breaking pressures recorded in Table 17-9, compared to those in Table 17-10, are likewise attributable to increased plastic flow, due to the slower rate of loading the specimens reported in Table 17-9.

With reference to Table 17-11, the substantial increase in the breaking pressure of glass-plastic laminates as the temperature is lowered from 120° to -60°F is due to the greater resistance to plastic flow at low temperatures and to the increase in modulus of rupture with decreasing temperatures.

TABLE 17-11

Temperature of Test Specimens: 120°, 75° and -60°F  
 Rate of Pressure Loading: 5 psi per min  
 Glass Size: 18 in. by 18 in. (Free Opening)

Glass-Plastic Combination	Type of Edge Mounting	Temperature of Test Specimen and Average Breaking Pressure, psi		
		120°F	75°F	-60°F
$\frac{1}{8}$ " glass $\frac{1}{8}$ " plastic $\frac{1}{8}$ " glass	Extended plastic, metal-reinforced	10	15	30
$\frac{1}{8}$ " glass $\frac{1}{8}$ " plastic $\frac{3}{16}$ " glass				
$\frac{1}{8}$ " glass $\frac{1}{8}$ " plastic $\frac{3}{16}$ " glass	Extended plastic, metal-reinforced	17	21	35

Figure 17-3 shows a test specimen of aircraft safety glass pressure-tested to destruction. The construction of the glass-plastic laminate comprised two lights of  $\frac{1}{8}$ -in. heat-strengthened glass and  $\frac{1}{8}$ -in.-thick



FIG. 17-3. Aircraft Safety Glass Tested to Destruction.

vinyl plastic with a metal-reinforced extended-plastic edge for mounting in the pressure-test chamber. As the picture shows, although the glass plates in the lamination are broken, the edge mounting provides firm anchorage of the plastic interlayer. Aircraft safety glass of this construction will afford protection from the atmospheric elements and the sudden release of internal pressure, should the glass become cracked or broken.

### Modulus of Rupture

The results of modulus of rupture tests (ultimate strength in bending), conducted on symmetrical glass-plastic laminates made with heat-strengthened glass, and vinyl plastic (containing 18 per cent dibutyl sebacate plasticizer) in different thicknesses and tested at different temperatures, are recorded in Table 17-12. The test specimens were  $3\frac{3}{4}$  in. wide and 11 in. long; distance between supports was 10 in. Each result recorded is the average of six determinations. As the results show, the ultimate strength in bending of laminated glass decreases with increasing plastic thickness and increasing temperature.

TABLE 17-12. BENDING TESTS

Glass Thickness, in.	Plastic Thickness, in.	Modulus of Rupture, psi			
		-60°F	0°F	80°F	125°F
$\frac{3}{16}$	0.075	24,900	21,600	10,600	6,570
	0.120	24,300	18,500	8,340	5,190
$\frac{1}{8}$	0.075	27,100	21,600	11,700	7,030
	0.120	26,000	20,100	9,610	5,710
$\frac{3}{16}$	0.075	28,600	24,300	11,030	8,120
	0.120	22,700	17,940	8,240	7,120

### Temperature Stability

Aircraft safety glass made with vinyl plastic will withstand temperatures up to 150°F for long periods of time without bubble formation, discoloration, or loss in light transmission. Although higher temperatures for short intervals of time may be used for deicing or defrosting purposes, it should be remembered that the plastic interlayer is organic and, to serve the purpose intended, must remain transparent. Accordingly, elevated temperatures much above 150°F are to be avoided.

### BULLET-RESISTING GLASS

Bullet-resisting glass is a composite structure consisting of multiple layers of plate glass bonded together with alternate layers of vinyl plastic to produce a structure of the required thickness. The same general principle employed in the manufacture of laminated safety glass is applicable for bullet-resisting glass, except that, as the thickness of the glass laminates is increased, the heating and cooling periods of the laminating cycle are materially increased, so as to avoid temperature differentials in the glass structure that will cause breakage. Also, the vinyl plastic interlayers usually contain about 20 per cent

TABLE 17-13. CHARACTERISTICS OF BULLET-RESISTING GLASSES OF VARIOUS THICKNESSES

Nominal Thickness (in.)	Visible Light Transmission, %	Bullet-Resisting Property				Results of Firing Tests
		Degree of Obliquity	Type of Gun	Type of Ammunition	Firing Distance, ft	
1½	82 to 84	0	0.38 Hammerless Harrington & Richardson	Standard	20	Impacted with 5 shots in an 8-in.-diameter circle; 3 of the bullets punctured the structure.
¾	81 to 83	0	0.38 Hammerless Harrington & Richardson	Standard	20	Impacted with 5 shots in an 8-in.-diameter circle; no bullets punctured the structure; little or no glass was spalled from back of structure.
¾	81 to 83	0	Colt D.A. 0.45	Standard	15	Of 5 shots in an 8-in.-diameter circle, 1 punctured the structure; sample bulged badly opposite points of impact.
1¼	81 to 82	0	Colt D.A. 0.45	Standard	15	Of 5 shots impacting within an 8-in.-diameter circle, none punctured the structure; little or no glass spalled from back of sample.
1¼	81 to 82	0	Smith & Wesson 0.357 Magnum	0.357 Magnum	20	Of 3 shots within an 8-in.-diameter circle, 1 bullet punctured the structure; considerable glass spalled from back of sample.

1½	80 to 82	0	Smith & Wesson 0.357 Magnum	0.357 Magnum	20	5 shots impacting in 8-in.-diameter circle failed to puncture the structure; very little if any glass spalled from back opposite points of impact.
1½	80 to 82	45	0.30-caliber Springfield Service Rifle	Armor-piercing	60	The bullet failed to puncture the structure; considerable glass was spalled from back opposite point of impact.
1½	80 to 82	45	0.30-caliber Springfield Service Rifle	Armor-piercing	600	The bullet failed to puncture the structure; little if any glass spalled from point opposite that of impact, complying with the tests set up in British Specification DTD 402, regarding penetration of the cellophane screen.
2	79 to 80	0	0.348 Winchester	Standard 150-gr bullet	60	Bullet failed to puncture the structure; only a small amount of glass spalled from back of sample.
3	73 to 75	0	0.30-caliber Springfield Service Rifle	Armor-piercing	60	Bullet failed to puncture the structure; only a very small amount of glass spalled from back of sample.
3	73 to 75	45	0.50-caliber machine gun	Armor-piercing	125	Bullet failed to puncture the structure; small amounts of glass spalled from sample opposite point of impact.
6	59 to 61	0	0.50-caliber machine gun	Armor-piercing	125	Bullet failed to puncture the structure, spalling small amounts of glass from sample opposite point of impact.



plasticizer, compared to 28 to 30 for regular safety glass. Further, the inner layers of plate glass going to make up the bullet-resisting structure are usually much heavier than thin plate glass used for the outside layers or for regular  $\frac{1}{4}$ -in. laminated safety glass.

Bullet-resisting glass is readily available in thicknesses of  $\frac{1}{2}$  to 3 in., and for special purposes has been furnished 6 in. thick. For calculating the weight of bullet-resisting glasses, it may be assumed that 13 psf per inch of thickness will be average and representative. Bullet-resisting characteristics and light transmission of glasses of different thicknesses are given in Table 17-13.

#### LAMINATED GLASS FILTERS

##### COLORED GLASS

The color and light-transmitting characteristics of soda-lime-silica glasses can be varied widely by incorporating small amounts of certain metal compounds in the glass batch, making available plate glass in colors of blue, green, golden amber, and flesh tint.

Depending on the coloring oxides used, these glasses are effective in selectively absorbing bands in the solar spectrum. This principle is employed in the manufacture of the commercially available heat-absorbing and ultraviolet-absorbing glasses, and also the blue, green, and red glasses used for light filters and decorative purposes.

Spectral-transmission curves which are typical for low iron plate; regular plate; heat-absorbing plate (blue-green); ultra-violet-absorbing plate (golden color); dark, medium, and light blue plate; green plate, and flesh-colored plate glasses are shown in Figs. 17-4 to 17-10, inclusive.

By laminating combinations of colored glasses with interposed transparent plastic layers, it is possible to obtain a variety of glass-plastic laminates which in effect serve as light filters to reduce or screen out almost completely certain portions of the spectrum, such as ultraviolet and infrared, normally present in the solar radiation.

Figure 17-11 shows the spectral transmission curves for (1) ultra-violet-absorbing plate glass 0.111 in. thick, (2) heat-absorbing plate glass 0.117 in. thick, and (3) the lamination of glasses (1) and (2) united with 0.015-in.-thick vinyl plastic interlayer.

##### COLORED PLASTIC

The incorporation of coloring agents in vinyl plastic or other plastics that can be bonded to glass presents another method for the preparation

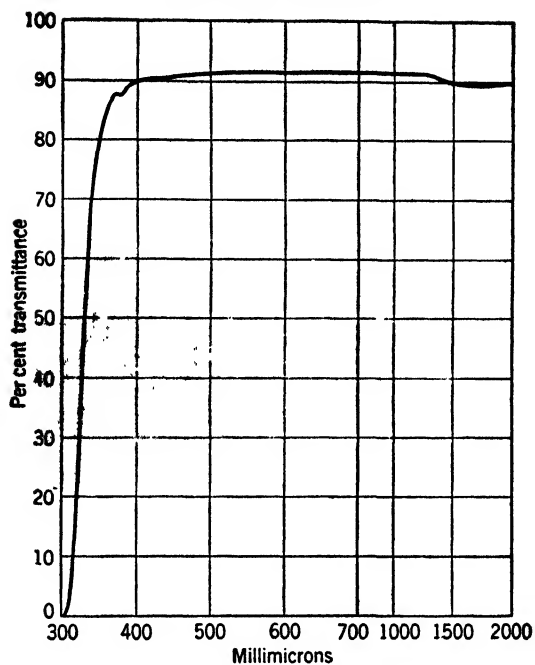


FIG. 17-4. Low Iron Plate 0.256 in. Thick, 0.02 per cent  $\text{Fe}_2\text{O}_3$ .

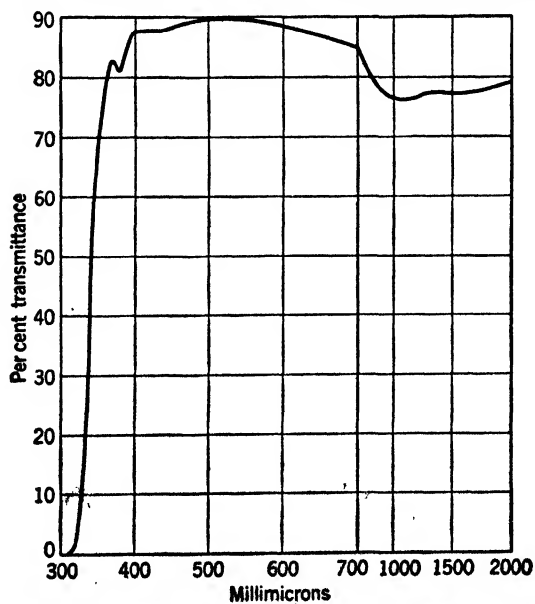


FIG. 17-5. Regular Plate 0.255 in. Thick, 0.1 per cent  $\text{Fe}_2\text{O}_3$ .

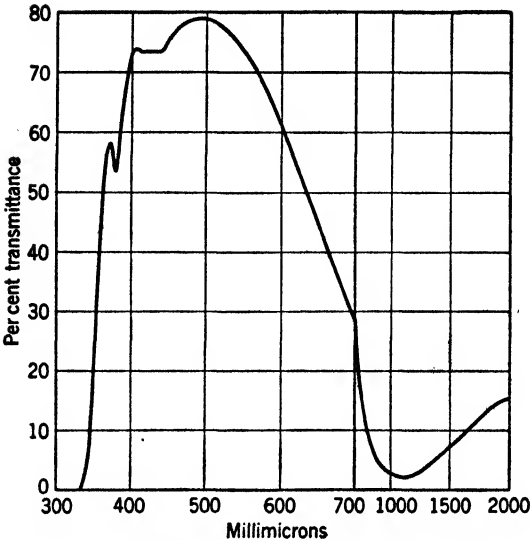


FIG. 17-6. Heat-Absorbing Plate 0.247 in. Thick.

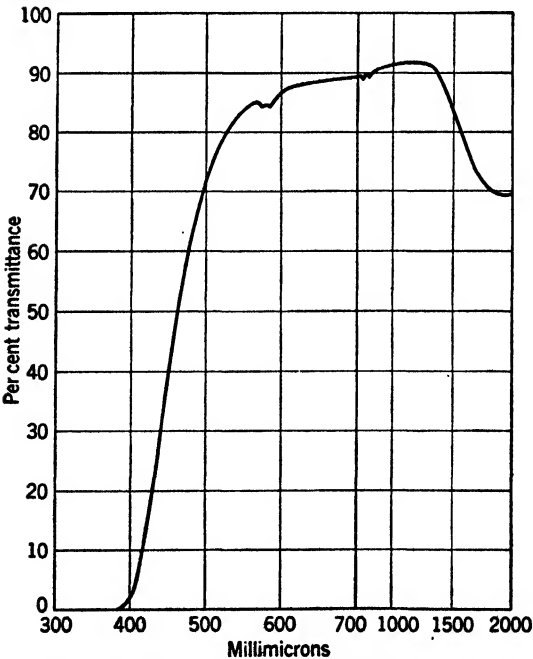


FIG. 17-7. Ultraviolet-Absorbing Plate 0.225 in. Thick.

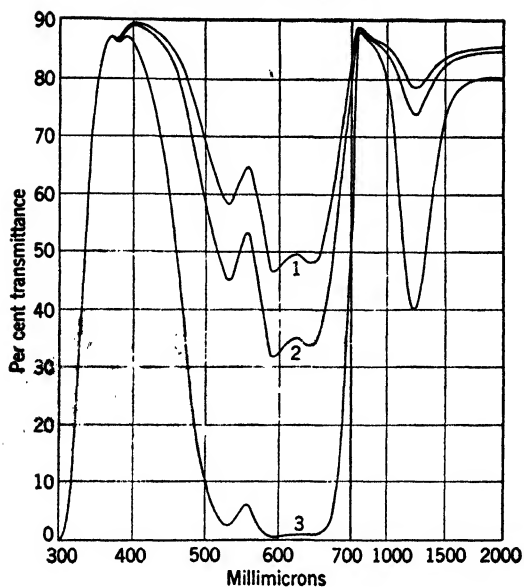


FIG. 17-8.

- (1) Light-blue plate 0.226 in. thick.
- (2) Medium-blue plate 0.225 in. thick.
- (3) Dark-blue plate 0.224 in. thick.

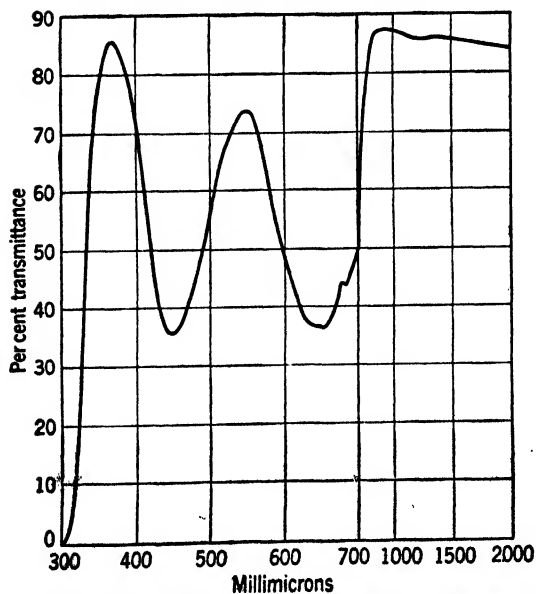


FIG. 17-9. Green Plate Glass 0.221 in. Thick.

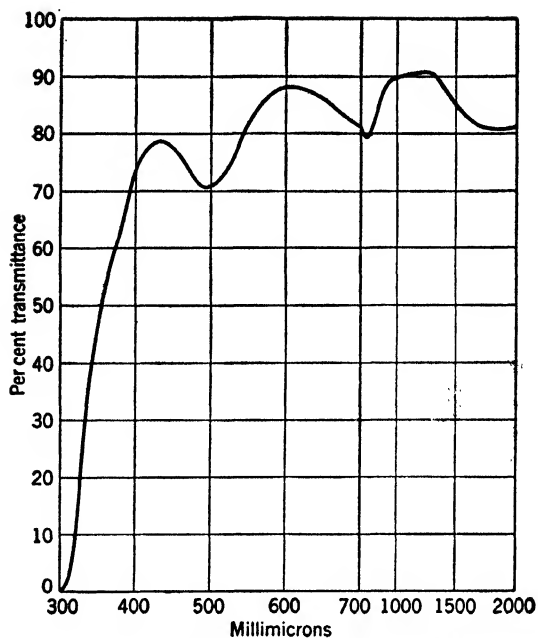


FIG. 17-10. Peach or Flesh-Color Plate Glass 0.226 in. Thick.

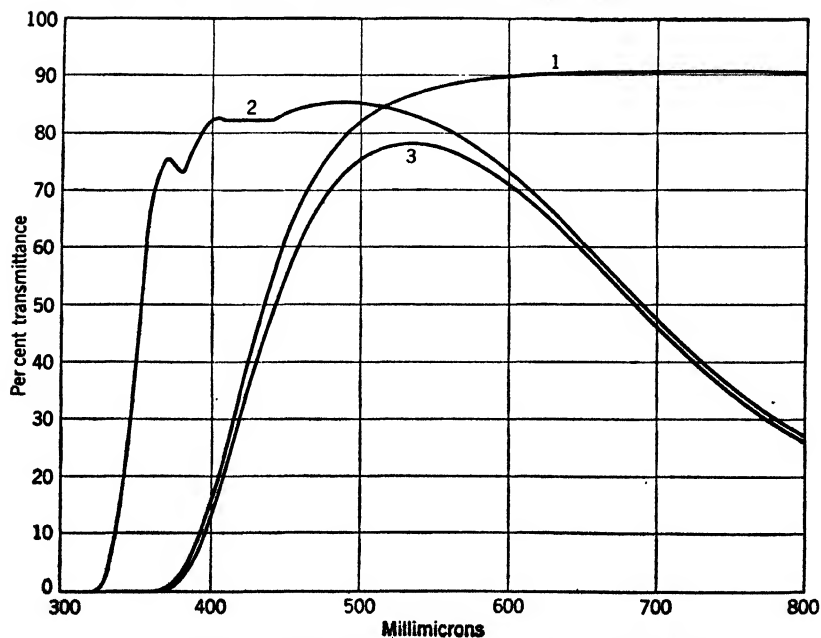


FIG. 17-11. (1) Ultraviolet-absorbing 0.111 in. thick. (2) Heat-absorbing 0.117 in. thick. (3) Lamination of (1) and (2) with 0.015 in. plastic.

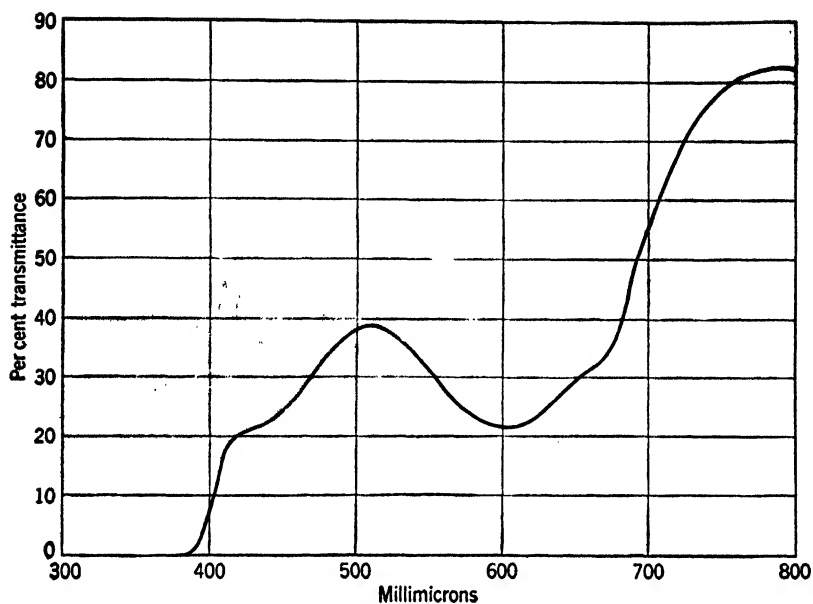


FIG. 17-12.  $\frac{1}{4}$  in. Lamination of Glass and Green Plastic.

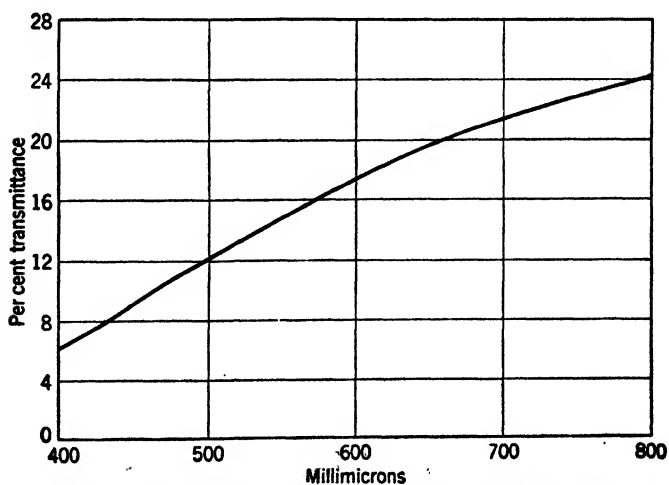


FIG. 17-13.  $\frac{1}{4}$  in. Lamination of Glass and Neutral Plastic.

of laminated-glass filters. Laminations of this type found valuable application during World War II as gunsight filters or shades to maintain the desired level of illumination; also, they are finding application

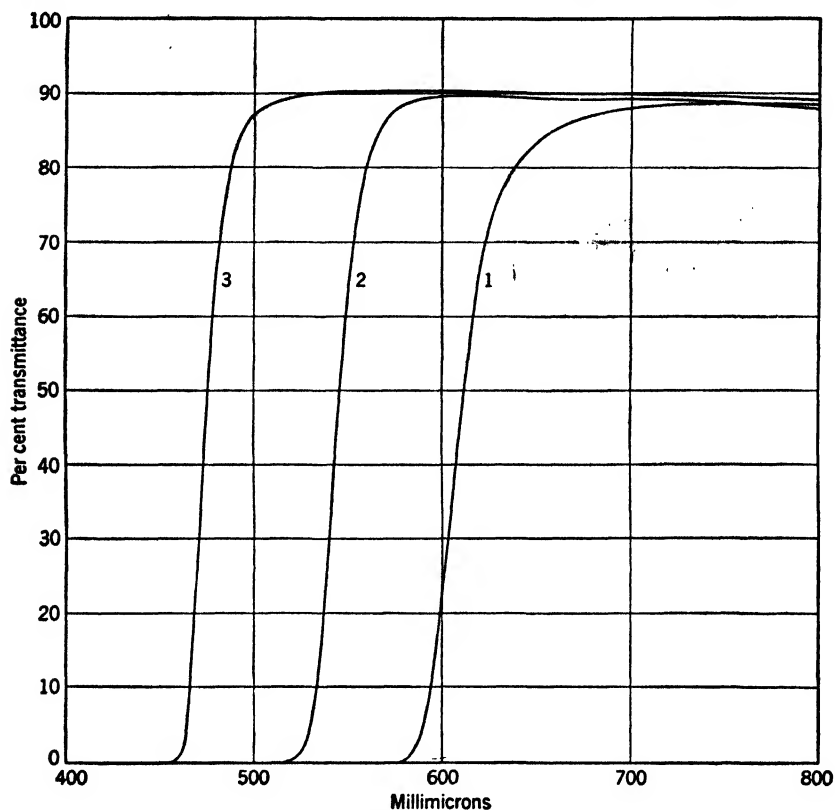


FIG. 17-14.

- (1) Glass—red plastic lamination.
- (2) Glass—orange plastic lamination.
- (3) Glass—yellow plastic lamination.

as sun visors, goggle lenses, camera filters, and for certain window glazings in motor vehicles.

Their manufacture usually consists in laminating the colored-plastic layer having the desired light-transmitting characteristics, between two lights of ordinary plate or sheet glass.

Figure 17-12 shows the spectral transmission of a laminated green filter made with two lights of regular  $\frac{1}{8}$ -in. plate glass, bonded together with an interposed layer of green-colored plastic. This type

of lamination has safety characteristics and serves as a sunshade for certain window glazings in motor vehicles.

Figure 17-13 shows the spectral transmission of a laminated neutral filter made with two lights of regular  $\frac{7}{8}$ -in. plate glass, bonded together with an interposed layer of neutral-colored plastic. Laminated

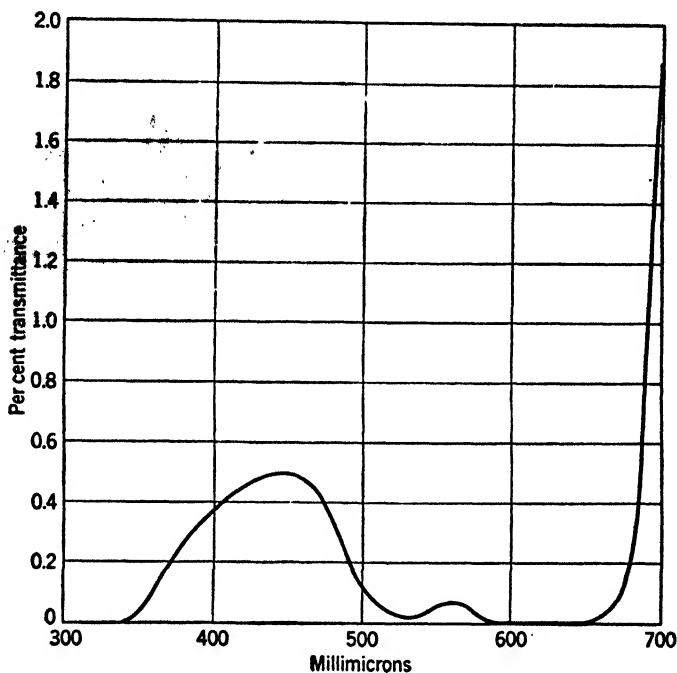


FIG. 17-15. Lamination of Two Lights  $\frac{1}{8}$  in. Dark-Blue Plate and Neutral Plastic 0.022 in. Thick.

filters of this kind find application as gunsight filters, sun visors and goggle lenses.

Figure 17-14 shows the spectral transmission of laminated (1) red, (2) orange, (3) yellow filters, made with two lights of glass, bonded together with interposed layers of the different colored plastics. Laminated filters of this type find application as light filters for photographic purposes.

#### COLORED GLASS AND PLASTICS

Obviously, a wide variety of light filters are possible by combining the light-filtering characteristics of colored glasses and plastics through



the process of lamination. Figure 17-15 shows the spectral transmission of a very low light-transmitting filter made by laminating two lights of  $\frac{1}{8}$ -in. dark-blue plate glass with an interposed layer of neutral plastic.

#### TRANSLUCENT GLASS-PLASTIC LAMINATES

Laminates of figured glasses are not commercially available owing to the difficulties involved in bonding the roughened or unflat surfaces. However, opal glasses are readily laminated, employing the same procedure as used for the manufacture of laminated safety glass.

Laminates of opal glass and plastics find application in the use of scientific instruments and for glazing certain openings where nondirectional lighting is desired and the safety feature of laminated safety glass is a requirement.

#### OPAQUE OR STRUCTURAL-GLASS-MASTIC LAMINATES

Structural-glass laminates find wide application for partitions and stiles in toilet-room construction, and also for the construction of table tops, counter tops, sign and glass-faced concrete masonry. For toilet-room construction, the laminates are usually made by bonding two lights of the structural glass with an interposed layer of adherent mastic approximately  $\frac{1}{8}$  in. thick. Counter- and table-top construction are usually made by laminating structural glass as the face or exposed surface to other structural materials, such as plywood, pressed board, and metal sheets, for reinforcing purposes and weight reduction per unit thickness of laminate.

The procedure for making the structural-glass laminates consists in applying a layer of mastic by means of metal rakes to each surface to be united. Depending on the mastic used, the coatings are allowed to dry somewhat; then the mastic-coated surfaces are placed adjacent and pressed firmly together, so that the finished lamination has a mastic interlayer approximately  $\frac{1}{8}$  in. thick.

Glass-faced masonry is made by bonding or laminating a layer of structural glass to a block of concrete masonry using a continuous layer of a water-proof mastic approximately  $\frac{1}{8}$  in. thick and further anchoring the glass facings by means of metal clips cast in the concrete block.

Glass-faced masonry offers outstanding properties, incorporating the beauty of structural glass and the required structural qualities of masonry. A glass-faced concrete masonry unit sold under the trade

name of Glastone is an example of this type of laminate. Figure 17-16 shows a section through the Glastone joint.

### COMPOSITE-GLASS-AIR-CELL STRUCTURES

Multiple layers of glass separated by air cells of predetermined thickness are referred to as insulating-glass windows. Although composite structures of this type are laminates comprising layers of glass and air,

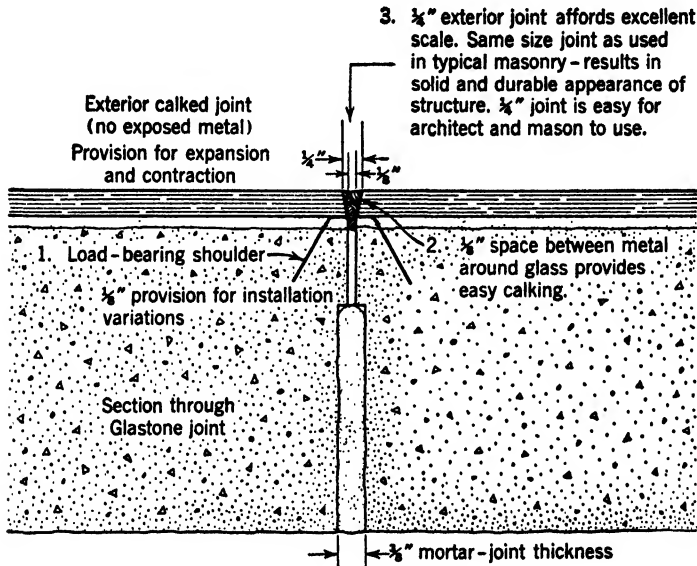


FIG. 17-16. Glastone. Concrete is Haydite or Waylite Which Tests More than 2000 psi.

their construction varies widely from glass-plastic or glass-mastic laminations. In the latter, the layers of unlike materials are bonded firmly together throughout the entire area, whereas the glass layers in the insulating window, separated a predetermined distance, are united or bonded at the margin only to form an air cell.

### CONSTRUCTION

Multiple-glass units for window-insulating purposes are available in various combinations of glass and air spaces. The number of lights of glass and air spaces and also the glass and air-space thicknesses will determine the insulation properties of the unit.

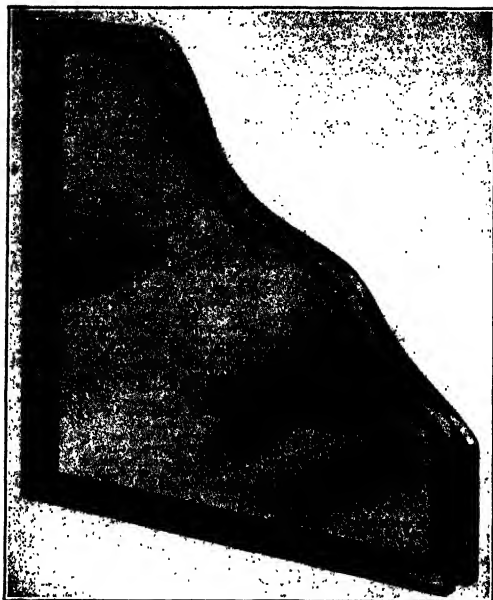


FIG. 17-17. Thermopane.



FIG. 17-18. Twindow.

The major production of multiple-glass units is made with regular plate and sheet glass to give high light transmission. However, by using one or more lights of the different types of glasses in the composite, special requirements such as the control of quality and quantity of light transmitted through the multiple glazed unit can be met.

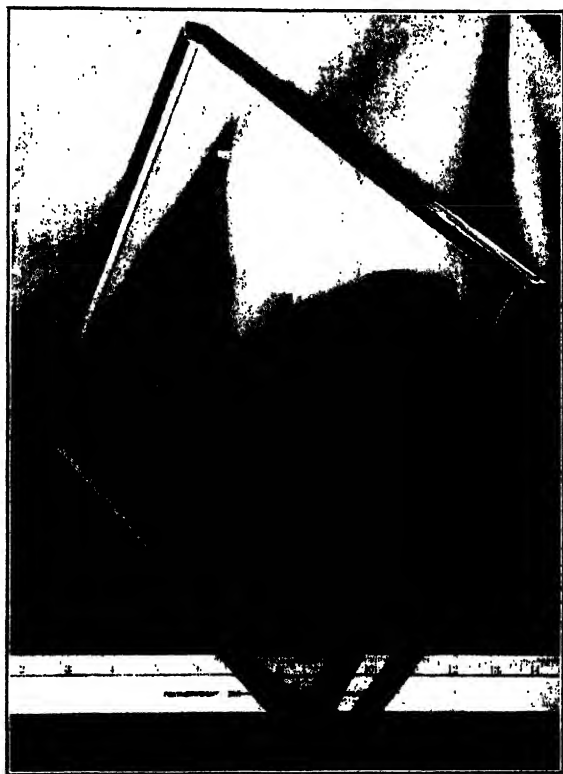


FIG. 17-19. Lustratherm.

Also by incorporating one or more lights of heat-strengthened glass or laminated safety glass, greater strength and added safety features can be realized; for example:

1. Heat-absorbing glass is effective in reducing the transmission of solar heat.
2. Ultraviolet-light-absorbing plate glass is effective in reducing the fading of fabrics, paintings, and the like, on display.
3. Wire glasses provide an efficient fire retardant.

4. Blue, green, golden, flesh-tinted, or peach-colored plate glasses afford decorative possibilities.
5. Figured glasses provide effective illumination without direct vision.
6. Heat-strengthened plate glass provides increased strength and impact resistance.
7. Laminated safety glass provides protection, affording greater resistance to impacting objects.

Although the fabricators of multiple-glass units, in general, have the same objectives in obtaining a glass-air-cell composite structure in which the air space or spaces are tightly sealed at the glass margin to exclude the infiltration of extraneous materials, such as moisture and dust, the methods for constructing the marginal seal vary widely with the different fabricators.

Figures 17-17, 17-18, 17-19 and 17-20 show four commercially available insulating-glass units supplied under the trade names of "Thermopane," "Twindow," "Lustratherm," and "Insulite."

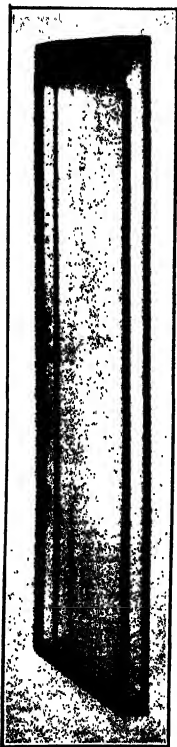


FIG. 17-20. Insulite.

#### THERMAL INSULATION

The thermal insulation of multiple-glass glazings is due to the combined resistances of glass and the relative still layers of air to the transfer of heat by conduction and convection. Since the resistance to heat flow through any path equals the reciprocal of its conductivity over the same path, the thermal transmittance or over-all coefficient of heat transmission  $U$  through a multiple-glass glazing is equal to  $1/R$  where  $R$  is the over-all resistance and is equal to the sum of the resistance of the air films (outside and inside), glass, and air space.

Thermal transmittance  $U$ , as determined by the guarded hot-box method, on single- and multiple-glass glazings, 12 in. by 12 in. and 30 in. by 30 in. in size, are given in Tables 17-14 and 17-15, showing the glass size, type of glass glazing, kind and nominal thickness of glass, number and width of air spaces, and thermal transmittance  $U$  (British thermal units per square foot per hour per degree Fahrenheit difference in temperature between the warm and cold sides) for wind velocities on the cold side of 3 and 15 mph.

TABLE 17-14. OVERALL TRANSMITTANCE  $U$  AT 3 AND 15 MPH WIND VELOCITIES ON THE COLD SIDE FOR GLASS GLAZINGS 30 IN. BY 30 IN. IN SIZE

Type of Glass Glazing	Kind and Nominal Thickness of Glass, in.	Number and Width Air Spaces, in.	$U$ at 3 mph	$U$ at 15 mph
Single	Sheet, 0.090	None	0.928	1.185
Single	Plate, 0.250	None	0.914	1.148
Double	Sheet, 0.090	1 (0.125)	0.657	0.759
Double	Sheet, 0.125	1 (0.125)	0.604	0.738
Double	Plate, 0.250	1 (0.125)	0.611	0.726
Double	Sheet, 0.090	1 (0.187)	0.588	0.711
Double	Sheet, 0.125	1 (0.187)	0.566	0.681
Double	Plate, 0.250	1 (0.187)	0.553	0.663
Double	Sheet, 0.090	1 (0.250)	0.558	0.668
Double	Sheet, 0.125	1 (0.250)	0.546	0.652
Double	Plate, 0.250	1 (0.250)	0.540	0.646
Double	Plate, 0.250	1 (0.500)	0.479	0.580
Triple	Plate, 0.250	2 (0.250)	0.396	0.468
Triple	Plate, 0.250	2 (0.500)	0.341	0.397

TABLE 17-15. OVERALL TRANSMITTANCE  $U$  AT 3 AND 15 MPH WIND VELOCITIES ON THE COLD SIDE FOR GLASS GLAZINGS 12 IN. BY 12 IN. IN SIZE

Type of Glass Glazing	Kind and Nominal Thickness of Glass, in.	Number and Width Air Spaces, in.	$U$ at 3 mph	$U$ at 15 mph
Single	Sheet, 0.090	None	0.926	1.166
Single	Plate, 0.250	None	0.835	1.140
Double	Sheet, 0.090	1 (0.125)	0.636	0.779
Double	Sheet, 0.125	1 (0.125)	0.630	0.770
Double	Plate, 0.250	1 (0.125)	0.615	0.755
Double	Sheet, 0.090	1 (0.187)	0.602	0.726
Double	Sheet, 0.125	1 (0.187)	0.596	0.723
Double	Plate, 0.250	1 (0.187)	0.576	0.694
Double	Sheet, 0.090	1 (0.250)	0.588	0.713
Double	Sheet, 0.125	1 (0.250)	0.584	0.705
Double	Plate, 0.250	1 (0.250)	0.568	0.688

Although the designed test conditions for making the heat-transmittance measurements were, for the cold side: 10°F and 3 and 15 mph wind velocity; for the warm side: 70°F with natural convection, the actual conditions of the individual runs varied from the designed conditions as follows:

Warm-side temperature	68.0 to 71.9°F
Cold-side temperature	9.6 to 11.8°F
Cold-side low velocity	2.5 to 3.3 mph
Cold-side high velocity	13.1 to 15.6 mph

Accordingly, the values of  $U$  given in the tables are the corrected values for 3 and 15 mph wind velocity on the cold side.

In Tables 17-14 and 17-15, the first column under the heading "Type of Glass Glazing," the word "Single" refers to one light of glass; "Double" to two lights of glass and one air space; "Triple" to three lights of glass and two air spaces.

#### ACKNOWLEDGMENT

The co-operation of members of the technical staffs of the Pittsburgh Plate Glass Company, American Window Glass Company, and Safetee Glass Company in supplying photographs of their multiple-glass units for reproduction is sincerely appreciated. Also I am indebted to my associates in the Libbey-Owens-Ford Glass Company for their helpful suggestions and assistance.

#### REFERENCES

1. A. T. FULLICKS, British Patent 15,303 (Aug. 20, 1885).
2. J. C. WOOD, British Patent 9972 (1905).
3. ÉDUARD BENEDICTUS, French Patent 405,881; British Patent 1790 (1910).
4. G. L. PIGMAN, *Aeronaut. Eng.* (Jan. 1945), R-4:9.

## Sandwich-Type Building Boards Having Insulation-Board Cores

ARMIN ELMENDORF

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Chicago, Ill.*

MORRIS LIEFF

*Elmendorf Corporation  
Chicago, Ill.*

Insulation boards are very well suited for use as cores in sandwich-type constructions because of their light weight, availability in relatively large areas, ease of laminating, low thermal conductivity, and low cost. Insulation boards may be used as cores in a number of ways. For example, several layers may be laminated together to the required thickness resulting in what will be called flat-grain cores. Other types of cores may be made by cutting strips of insulation board to a width equal to the thickness of core desired and then placing these side by side on their edges. The resultant cores are referred to herein as end-grain cores.

In the text, for convenience of discussion, sandwich-type building boards are grouped under two main headings, depending on the nature of the core used, namely:

- (a) Sandwiches having flat-grain cores
- (b) Sandwiches having end-grain cores

### **SANDWICHES HAVING FLAT-GRAIN INSULATION-BOARD CORES**

The conventional method for using insulation boards in sandwich constructions consists of gluing together several layers of insulation board to which are then laminated higher-density face materials. Such materials as sheet metal, lignocellulose hardboard and cement-asbestos board have been used as facings. Sheet-metal faces on conventionally laminated cores have proved unsatisfactory because they can be readily peeled off the core. Cement-asbestos-faced boards, on the other hand, have been widely and successfully used.



Such a product illustrated in Fig. 18-1 appears on the market in several thicknesses, and consists of  $\frac{1}{8}$ -in. cement-asbestos board, light gray in color, bonded to the laminated insulation-board core, with a

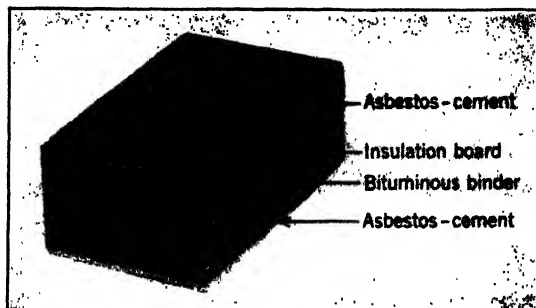


FIG. 18-1. Insulated Cement-Asbestos Sandwich-Type Panel. (Courtesy Celotex Corporation)

moisture-proof vapor-resistant bituminous adhesive. It presents to the building trade a single-thickness exterior wall material that replaces several separately applied layers such as siding, sheathing, building

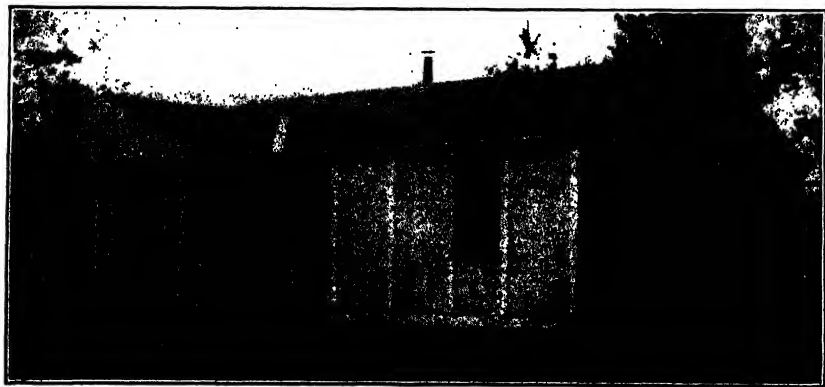


FIG. 18-2. House Made of Insulated Asbestos-Cement Sandwich-Type Panels (Cemesto) with Vertical Framing. (Courtesy Celotex Corporation)

paper, insulation, and lath and plaster used in ordinary wall construction.

The cement-asbestos-faced slab provides insulation and the exterior and interior finish of the building. It requires no painting and contributes structural strength to the framing. This slab is used for exterior walls, partitions, and ceilings in permanent and temporary

housing, tourist cabins, farm buildings, and small business structures. On industrial buildings it is used for the exterior as a curtain wall or as an inside lining material and as roof decking.

Figures 18-2 and 18-3 illustrate two small houses made of Cemesto, an insulated cement-asbestos sandwich-type panel. Figure 18-2 shows the use of the panels placed vertically with a vertical wood framing member at each joint, whereas in Fig. 18-3 the panels are placed horizontally, and vertical framing is used only at the panel ends.

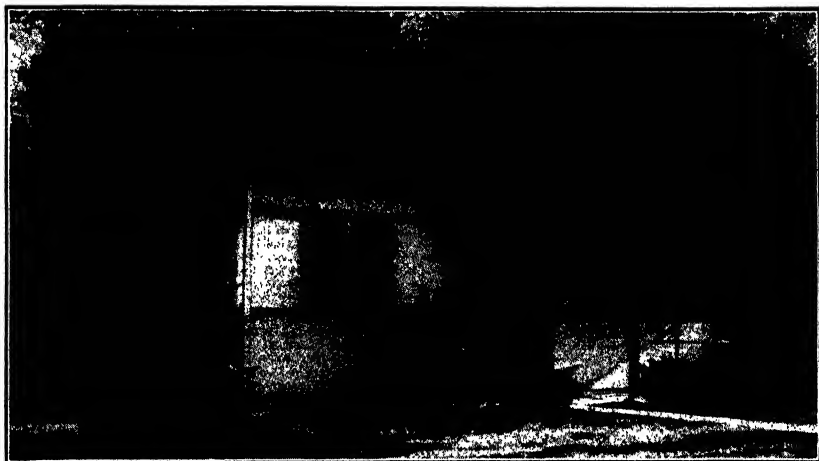


FIG. 18-3. House Illustrating Horizontal Use of Sandwich Panels. (Courtesy Celotex Corporation)

In the so-called horizontal-rail-type home illustrated in Fig. 18-3, ten specially prefabricated wood columns are set up as shown in Fig. 18-4. These are held together at their mid-points with horizontal wood rails and at their tops with plywood girders. The sandwich panels and prefitted window frames complete with sash are fitted into the framing. Roof trusses are installed bringing the structure to the stage illustrated in Fig. 18-5. A conventional roof is then applied, producing the completed home of Fig. 18-3.

In the so-called post-and-girder-type home of Fig. 18-2, the wall framing consists of T-shaped wood posts, set 4 ft apart which are nailed to preassembled girders. The resultant wall framing is assembled on the floor, placed upright into position, and fastened to the wood sill. Complete window and door units with T-shaped jambs to fit the posts are set in place and fastened to the posts. Preassembled roof trusses are

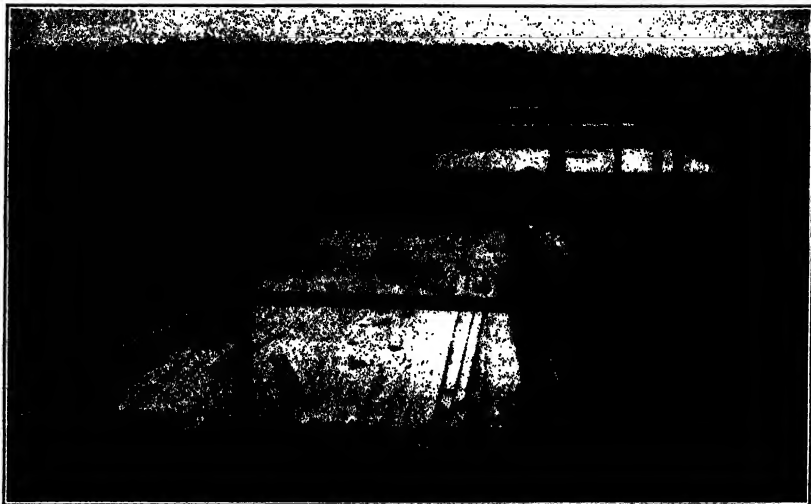


FIG. 18-4. Wood Framing Showing Vertical Columns, Horizontal Rails, and Plywood Girders. (Courtesy Celotex Corporation)

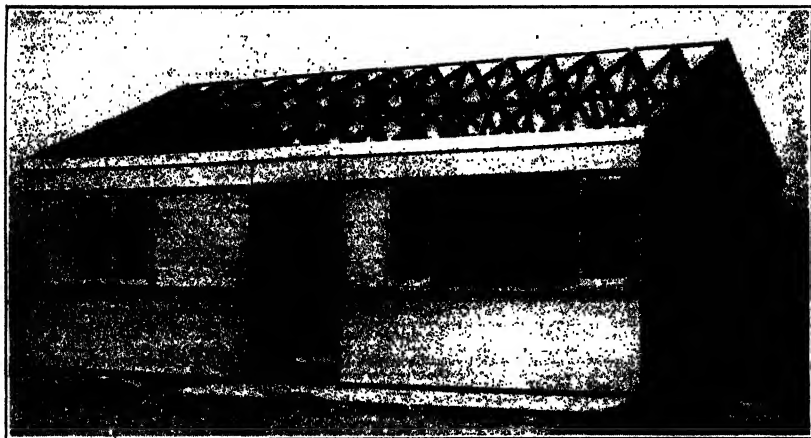


FIG. 18-5. Partially Completed Horizontal-Rail-Type House Shown in Fig. 18-3. (Courtesy Celotex Corporation)

erected on the girders. The sandwich panels are placed as shown in Fig. 18-6 and fastened with nails or screws. All joints are filled with

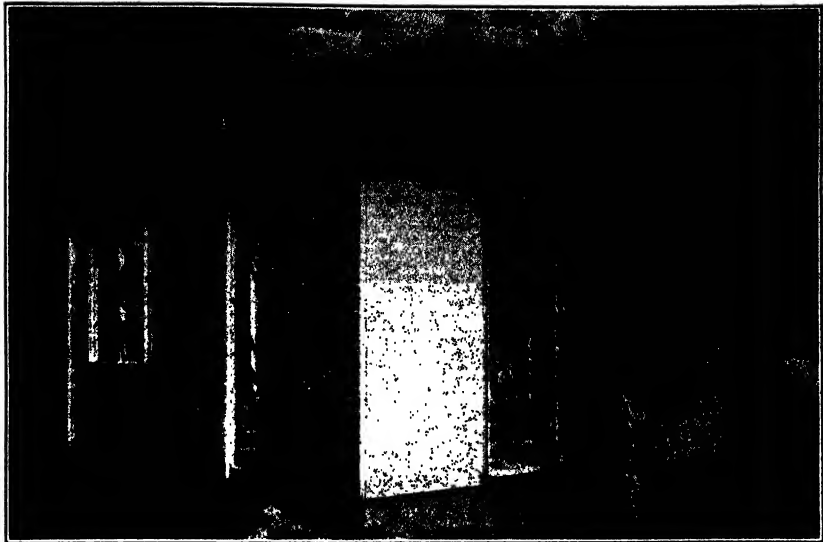


FIG. 18-6. Placing of Panels in Post-and-Girder House Illustrated in Fig. 18-2.  
(Courtesy Celotex Corporation)

a calking compound or calking tape, and wood-batten strips are nailed over the vertical joints.

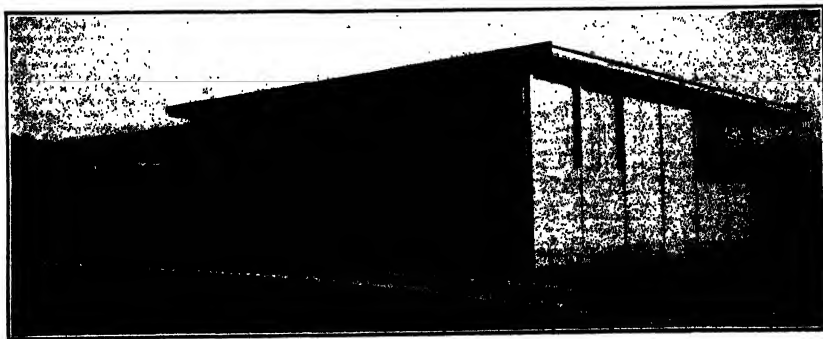


FIG. 18-7. House Using Sandwich Panels (Cemesto) in Vertical Construction.

Figure 18-7 shows an interesting house of modern design using the solar principle of wide windows, flat roof with large overhang, and vertical construction. This type produces low-cost, attractive, and

## Sandwich-Type Building Boards



FIG. 18-8. Sandwich Panels Used as Roof Decking of an Industrial Plant.  
(Courtesy Celotex Corporation)

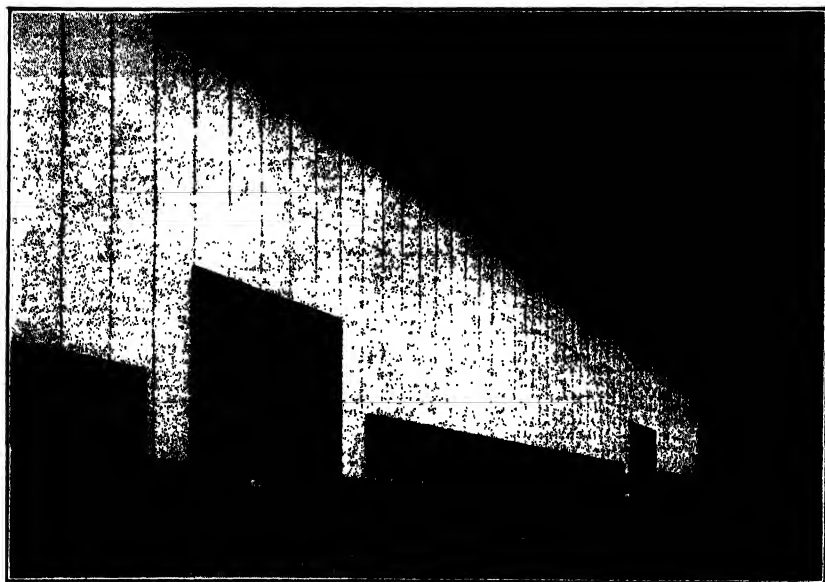


FIG. 18-9. Sandwich Panels Used as Exterior Walls of an Industrial Building.  
(Courtesy Celotex Corporation)

## Strength Properties, Flat-Grain Core Sandwiches 623

comfortable homes that can be quickly and economically erected. Figure 18-8 illustrates the use of insulated cement-asbestos sandwiches for roof decking of an industrial building, and Fig. 18-9 shows the same material used for walls of a factory building.

**Insulating Value.** Table 18-1 summarizes the insulating values of Cemesto board.

TABLE 18-1. INSULATING VALUES OF CEMESTO, AN INSULATED ASBESTOS-CEMENT SANDWICH

Over-all thickness	1½"	1¾"	2"
Insulating board core thickness	⅞"	1⅝"	1¾"
Conductance of core ( $K = 0.338$ Btu/in.	0.38	0.25	0.19
Coefficients, air-to-air ( $U$ value)			
Inside walls or partitions	0.25	0.19	0.15
Outside walls	0.28	0.20	0.16
Surface-to-surface coefficients (conductance)	0.36	0.24	0.18

**Weight.** Table 18-2 gives the weight of various thicknesses of Cemesto board.

TABLE 18-2. WEIGHT OF CEMESTO PANELS OF VARIOUS THICKNESSES

Thickness, in.	Wt psf
1½	4.0
1¾	4.8
2	5.3

## STRENGTH PROPERTIES, CEMENT-ASBESTOS FACES

Table 18-3 summarizes some of the strength properties of the cement-asbestos faces used in Cemesto.

TABLE 18-3. PROPERTIES OF CEMENT-ASBESTOS FACES

	Parallel to Machine Direction	Across Machine Direction
Tensile strengths, psi	1620	825
Modulus of rupture, psi	4140	3600
Specific gravity	1.65	

## STRENGTH PROPERTIES, FLAT-GRAIN CORE SANDWICHES

**Bending Strength.\*** Results of uniform loading tests on flat-grain sandwiches (Cemesto) in which the panels were nailed to a supporting wood framework along all four edges are shown in Table 18-4.

\* The majority of the strength tests on Cemesto were conducted in the laboratories of the R. W. Hunt Company and are presented through the courtesy of the Celotex Corporation.

TABLE 18-4

Thickness of Panel, in.	Size of Panel, ft	Maximum Load, psf
1½	4 x 12	133
1¾	4 x 8	200

In deflection and recovery tests a 1¾-in. panel, 4 ft by 8 ft, was nailed to wooden supports along all four edges. A uniformly distributed load of dry sand, 75 psf, was applied to the top surface for a 24-hr period and then removed. Loading took 1½ hr, and unloading took 3 hr. The results are summarized below:

<i>Deflection under load of 75 psf:</i>	
Immediately after application of load	0.341"
24 hr after application of load	0.402"
<i>Set after removal of load (deflection after removal of load):</i>	
Immediately after removal of load	0.075"
24 hr after removal of load	0.023"

Simple beam tests with concentrated load at center, made with machine direction of board across supports, on specimens 5 in. wide and 30 in. long, on a 28-in. span, are summarized in Table 18-5.

TABLE 18-5

Thickness of Panel, in.	Maximum Load, lb	Stiffness, Load per 0.1 in. Deflection
1¾	212	134
1½	155	72

**Tensile strength.** Table 18-6 shows the tensile strength of flat-grain sandwiches (Cemesto) of several thicknesses. The breaking section of the specimens was 1 in. wide.

TABLE 18-6

Nominal Thickness, in.	Actual Thickness, in.	Total Thickness of Asbestos-Cement Facings, in.	Direction	Breaking Load, lb per in. Width
1½	1.129	0.283	Lengthwise	211
1½	1.133	0.280	Crosswise	213
1¾	1.581	0.326	Lengthwise	232
1¾	1.580	0.327	Crosswise	242
2	2.107	0.320	Lengthwise	247
2	2.110	0.315	Crosswise	244

## Strength Properties, Flat-Grain Core Sandwiches 625

**Edge Compression.** Edge-compression tests made as illustrated in Fig. 18-10 are given in Table 18-7. Specimens were  $3\frac{1}{2}$  in. high and  $1\frac{3}{4}$  in. wide.

TABLE 18-7

Thickness, in.	Crushing Strength, lb per in. Width
1.106	1,235
1.596	1,700
2.014	1,790

**Column Loading.** Loading tests made on a 4-ft-by-8-ft panel 2 in. thick on end gave a maximum load of 6775 lb per foot of width.

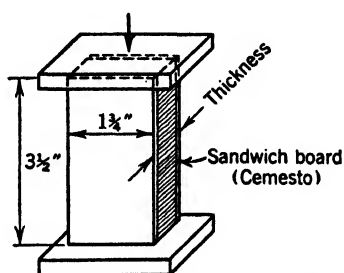


FIG. 18-10. Edge-Compression Test of Sandwich Board.

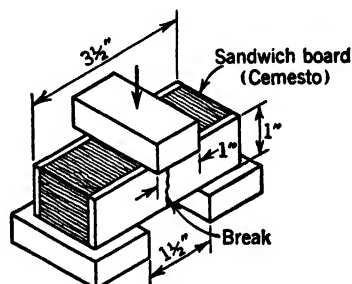


FIG. 18-11. "Shear" Test of Sandwich Board.

**Shear.** Shear-strength data, obtained by testing small specimens of cement-asbestos-faced sandwiches 1 in. by  $3\frac{1}{2}$  in. and of various thicknesses as illustrated in Fig. 18-11, are summarized in Table 18-8. Specimens were supported on blocks  $1\frac{1}{2}$  in. apart with cement-asbestos faces vertical. The load was applied through a rectangular block 1 in. wide centered between the supports. Height of the specimens was 1 in.

TABLE 18-8

Nominal Thickness, in.	Actual Thickness, in.	Maximum Load, lb	Shearing Strength, psi
$1\frac{1}{8}$	1.124	453	201
$1\frac{5}{16}$	1.597	674	211
2	2.020	1117	277

**Nail Holding.** Tests made to determine the nail-holding strength of flat-grain sandwiches (Cemesto) were carried out in such a manner as to tend to shear off the nails between the sandwich and a wooden member to which it was nailed. Actually the nails bent gradually and



then were pulled through the outer surfacing of cement-asbestos. Common nails were driven so that the under surface of the head was flush with the outer surface of sandwich face. No holes were drilled for the nails. The results of these tests are summarized in Table 18-9.

TABLE 18-9. LATERAL NAIL-HOLDING POWER

Test No.	Thickness of Cemesto, in.	Number of Nails	Size of Nails	Maximum Load, lb	Nail Penetration in Wood, in.	Load per Nail, lb
1	1 $\frac{1}{8}$	8	6d	2070	$\frac{7}{8}$	259
2	1 $\frac{1}{16}$	8	8d	1930	1 $\frac{5}{16}$	241
3	1 $\frac{1}{8}$	14	6d	2830		*
4	1 $\frac{1}{16}$	14	8d	3235		*
5	1 $\frac{1}{8}$	10	8d	3015	1 $\frac{3}{8}$	301
6	1 $\frac{1}{16}$	10	10d	3700	1 $\frac{1}{4}$	370
7	2	10	12d	3990	1 $\frac{1}{4}$	399
8	1 $\frac{1}{8}$	22	6d	3285		*
9	1 $\frac{1}{16}$	22	8d	3810		*
10	2	22	10d	4515		*

\* Loads per nail for nailing into top and bottom framing members are not computed since deflection caused uneven loads in the variously spaced nails.

Tests were also made to determine the load necessary to pull a common nail through the sandwich. In this test the load was applied perpendicular to the cement-asbestos faces. In the previous test the load was applied parallel to the sandwich face. A specimen 18 in. square was centered over an opening 2 in. square. A common nail was driven through the center of the specimen, and the load necessary to pull the nail through the specimen was measured. Test data are summarized in Table 18-10.

**Screw Holding.** Screw-holding tests carried out as illustrated in Figs. 18-12 and 18-13 are summarized in Tables 18-11 and 18-12.

**Impact Tests.** A flat-grain sandwich (Cemesto) panel 1 $\frac{1}{16}$  in. thick, 4 ft by 12 ft in size, supported on all its edges by being nailed to a wooden framework, on being subjected to the impact of a 60-lb sandbag, as outlined in the Bureau of Standards Building Materials and Structures report BMS-2, gave the results shown in Table 18-13. The sandbag was first dropped 6 in., and then additional drops were made by increments of 6 in. until failure occurred.

**Rain-Penetration Tests.** Cemesto panels, 1 $\frac{1}{16}$  in. thick, having both vertical and horizontal joints, were exposed for 5 days to a heavy rain, in a rain-penetration testing chamber. No penetration of moisture took place.

# Strength Properties, Flat-Grain Core Sandwiches 627

TABLE 18-10. LOAD TO DRAW COMMON NAIL THROUGH SANDWICH

Nominal Thickness of Cemento, in.	Nail Size	Diameter of Nail, in.		At 0.1 in. Deformation of Top Surface	Load, lb	
		Head	Shank		Maximum, with Nail Head Shearing Top Surface	Maximum, with Nail Head Cracking Bottom Surface
1½	6d	0.255	0.112	130	170	250
1½	8d	0.273	0.131	158	150	213
1½	10d	0.299	0.147	169	204	216
1¾	8d	0.273	0.131	157	192	220
1¾	10d	0.299	0.147	210	241	257
1¾	12d	0.293	0.148	167	155	221
2	10d	0.299	0.147	181	244	265
2	12d	0.293	0.148	198	220	256
2	16d	0.343	0.167	177	287	270
2	20d	0.392	0.192	245	356	330

In every test, nail head sheared through the top surface of the Cemento without causing any additional cracking. When passing through bottom surface, nail head caused radial cracks which ranged from ¾ in. to 1¾ in. in length.

TABLE 18-11. SCREW-HOLDING TESTS—STEEL TO CEMENTO

Nominal Thickness of Cemento, in.	Size of Wood Screw	Maximum Load, lb	Load per Screw, lb
1	1" #10	740	370
	1" #12	725	362
	1" #14	780	390
1¾	1¼" #12	770	385
	1¼" #14	820	410
	1¼" #16	885	442
2	1¾" #14	800	400
	1¾" #16	830	415
	1¾" #18	840	420

TABLE 18-12. SCREW-HOLDING TESTS—WOOD TO CEMENTO

Nominal Thickness of Cemento, in.	Size of Wood Screw	Maximum Load, lb
1	2½" #14	1955
	2½" #16	1730
	2½" #18	1400
1¾	3" #14	2375
	3" #16	2295
	3" #18	2440
2	3½" #14	2845
	3½" #16	3225
	3½" #18	3050

TABLE 18-13. IMPACT WITH 60-LB SANDBAG

Location	Height of Drop at Failure, in.
Center of panel	42
3 feet from end, 2 feet from sides	42
3 feet from other end, 2 feet from sides	48

The panel failed by fracturing the top surface over an area 10 in. to 13 in. in diameter. The bottom surface showed diagonal cracks.

**Cutting Cemesto.** Cement-asbestos sandwiches can be cut with abrasive disks or regular wood-cutting cross-cut circular saws. They can also be cut with a handsaw, when no other method of cutting in the field is available.

**Painting.** The light-gray natural color of the cement-asbestos board provides good light reflection and eliminates the necessity for painting.

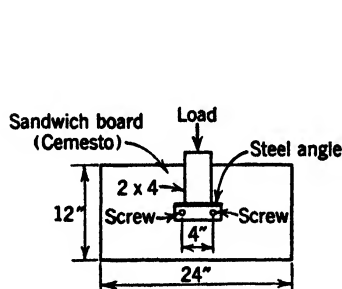


FIG. 18-12. Tests of Screw-Holding Power against Steel.

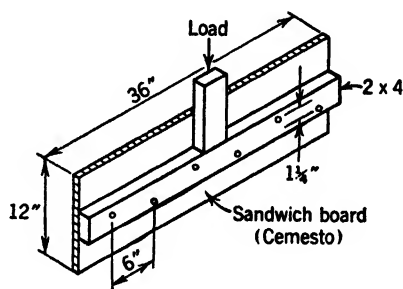


FIG. 18-13. Tests of Screw-Holding Power against Wood.

If color is desired, the cement-asbestos may be painted with water paint or with oil paint if a limeproof coat is first applied.

#### SANDWICHES HAVING END-GRAIN INSULATION-BOARD CORES

Sandwich-type constructions having ordinary insulation-board cores do not have high bending strength. This weakness is owing to the low shear strength parallel to the surface of the board which causes the board to fail in shear when it is bent before the maximum strength of the outer layers is reached. Weakness in shear also brings with it low stiffness.

As papermaking machinery is generally used for felting the fibers to building-board thicknesses, most of the fibers lie in planes parallel to the faces of the board. This fiber orientation affords little resistance

to shear, but, if the insulation board is cut into strips and these strips are glued on edge between the sandwich panel faces, a large proportion of the fibers lie in planes at right angles to the faces of the panel. When a panel having such an end-grain core is subjected to bending, it is necessary to tear through many fibers to produce shear failure, so that superior strength would be expected when the fibers are oriented in this manner.

#### BENDING STRENGTH OF SANDWICHES WITH END-GRAIN CORES

Experiments made in the laboratory of the Elmendorf Corporation show conclusively that slabs having various kinds of facing materials bonded to end-grain insulation-board (Celotex) cores, as illustrated in Fig. 18-14, are very much stronger and stiffer than similar slabs in

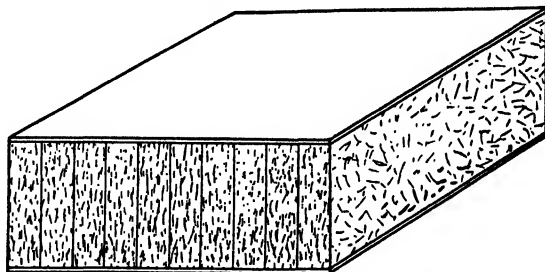


FIG. 18-14. Sandwich Having End-Grain Insulating-Board Core.

which the cores are made conventionally with the insulation-board layers parallel to the faces. The results of tests made on end-grain and flat-grain core constructions are shown in Tables 18-14 and 18-16.

End-grain sandwich-type constructions are generally two to six times stronger and stiffer in bending than corresponding flat-grain panels. The highest test values were obtained with faces of relatively high tensile strength and high modulus of elasticity such as steel. Intermediate values were obtained with faces of moderate tensile strength such as wood. The lowest values were obtained when relatively weak face materials were used, such as gypsum board and chip board. Such panels tested in bending fail in tension or compression of the faces, and the difference in strength between panels having end-grain cores and similar panels having flat-grain cores is not so marked.

Table 18-15 summarizes the results of bending tests on end-grain sandwiches having lignocellulose hardboard faces.

It is significant, as shown in Table 18-16, that as the thickness increases so does the superiority of the slabs having end-grain cores over

TABLE 18-14. BENDING TESTS ON SANDWICH-TYPE CONSTRUCTIONS HAVING BOTH FLAT-GRAIN AND END-GRAIN INSULATION-BOARD (CELOTEX) CORES AND VARIOUS TYPES OF FACES

Width of Specimens: 5 in. Span: 28 in. Tested as Simple Beam													
Faces	Core, Insulation Board (Celotex), in.	Flat Grain					End Grain					Ratio, End Grain to Flat Grain	
		Thick-ness, in.	Maxi-mum Load, lb	Stiffness Load per 0.1 in. Deflection, lb	Type of Failure	Thick-ness, in.	Maxi-mum Load, lb	Stiffness Load per 0.1 in. Deflection, lb	Type of Failure	Maxi-mum Load, lb	Deflec-tion, in.		
3/4" yellow pine	1	1.23	213	51	Horizontal shear in core	1.28	850	105	Tension failure in bottom face	4.0	2.1		
3/4" yellow pine	1 1/2	1.66	276	65	Horizontal shear in core	1.76	1280	183	Tension failure in bottom face	4.6	2.8		
3/4" chip board (Kenmore)	1	1.24	125	30	Horizontal shear in core	1.25	220	45	Tension failure in bottom face	1.8	1.5		
3/4" chip board (Kenmore)	1 1/2	1.69	203	52	Horizontal shear in core	1.75	370	95	Tension failure in bottom face	1.8	1.8		
3-ply becker board	1	1.28	194	26	Horizontal shear in core	1.28	308	42	Tension failure in bottom face	1.6	1.6		
3-ply becker board	1 1/2	1.68	247	37	Horizontal shear in core	1.77	452	95	Tension failure in bottom face	1.8	2.6		
3/4" gypsum board	1	1.67	184	60	Compression failure in face	1.67	261	122	Compression failure in face	1.4	2.0		
3/4" gypsum board	1 1/2	2.13	277	86	Compression failure in face	2.13	406	230	Compression failure in face	1.5	2.7		
4-ply 30-pt. Kraft	1	1.12	165	49	Horizontal shear in core	1.16	316	134	Upper face buckled	1.9	2.7		
1/4" asbestos board (Celotex)	1 1/2	1.60	255	96	Tension failure in lower face	1.53	257	216	Tension failure in lower face	1.1	2.3		

TABLE 18-15. BENDING TESTS ON PANELS HAVING END-GRAIN CORES AND VARIOUS HARDBOARD FACES

Width of specimens: 5 in.

Span: 28 in.

Tested as Simple Beam

Faces	Insulation Board Core	Thick-ness, in.	Maxi-mum Load, lb	Load per 0.1 in. Deflection, lb	Type of Failure
Masonite, ¼" Deluxe quarter board	1" end grain (Celotex)	1.32	607	100	Tension failure in bottom face
Masonite, ¼" Deluxe quarter board	1½" end grain (Celotex)	1.80	1002	196	Tension failure in bottom face
Weatherwood, ¼" quarter board	1" flat grain (Weather-wood)	1.44	170	55	Horizontal shear in core
Masonite, ⅛" Presdwood	1" end grain (Celotex)	1.27	350	62	Tension failure in bottom face
Masonite, ⅛" Presdwood	1½" end grain (Celotex)	1.66	657	143	Tension failure in bottom face

the slabs having flat-grain cores. The ratio of the stiffness of the former to that of the latter for slabs faced with 26-gage steel is 3.1 for the 1-in. thickness, 4.9 for 1½-in., and 5.6 for 2-in. thickness. In other words, steel-faced slabs 2 in. thick, having end-grain cores, when used as roof decking, will deflect only about one sixth as much under the same load as similar slabs having flat-grain cores. When faced with 22-gage steel a steel-faced slab having an end-grain core will carry about seven times the load for a given deflection as a similar slab having flat-grain insulation board as the core. These data are shown graphically in load-deflection curves plotted in Fig. 18-15. The  $EI$  or stiffness factors were obtained from the load-deflection curves by selecting a load, finding the deflection at that load from the curve, and then substituting these values in the beam formula:

$$y = \frac{Pl^3}{48EI}$$

in which

$y$  = deflection

$P$  = center load

$L$  = span

$E$  = modulus of elasticity

$I$  = moment of inertia

TABLE 18-16. STRENGTH OF INSULATED-STEEL SANDWICH-TYPE PANELS

Width of Specimens: 5 in.

Span: 28 in.

Tested as Simple Beam

Core, Insulation Board (Calotex), in.	Metal Faces, P.G.	End Grain Specimens					Flat Grain Specimens					Ratio of End Grain to Flat Grain	
		Thick-ness, in.	Maxi-mum Load, lb	Stiffness 0.1 in. Deflec-tion, lb	Stiffness Factor $EI$ for 5 in. width	Thick-ness, in.	Maxi-mum Load, lb	Stiffness 0.1 in. Deflec-tion, lb	Stiffness Factor $EI$ for 5 in. width	Maxi-mum Load	Stiff-ness		
2	22-gage	1.96	1,960	750	3,440,000	1.97	292	105	480,000	6.7	7.1	3.5	3.1
2	28-gage	1.94	1,000	545	2,500,000	1.97	244	98	448,000	4.1	5.6		5.6
1½	22-gage	1.49	1,540	575	2,640,000	1.50	234	85	389,000	6.6	6.8		6.8
1½	26-gage	1.46	800	340	1,560,000	1.50	198	70	320,000	4.0	4.9		4.9
1	22-gage	0.98	944	285	1,305,000	1.03	186	70	320,000	5.1	4.1	3.5	4.1
1	26-gage	0.96	498	175	803,000	1.00	144	55	252,000	5.1	3.1		3.1

Table 18-17 summarizes the results of bending tests on specimens made with 1½ in. and 2 in. end-grain cores faced with steel sheets of various thicknesses.

TABLE 18-17. BENDING STRENGTH OF INSULATED-STEEL SANDWICH-TYPE PANELS HAVING END-GRAIN INSULATION BOARD (CELOTEX)

Width of specimens: 5 in.

Span: 28 in.

Tested as Simple Beam

Metal Faces, Galvaneal	Core, End Grain Insulation Board (Celotex), in.	Panel Thickness	Maximum Load, lb	Stiffness, Load per 0.1-in. Deflection, lb	Stiffness Factor EI for 5-in. Width
24-gage	2	2.03	992	625	2,860,000
22-gage	2	2.08	.....	725	3,320,000
26-gage	1½	1.51	797	460	2,100,000
24-gage	1½	1.51	758	532	2,440,000
22-gage	1½	1.67	1,070	630	2,880,000

Table 18-18 summarizes the results obtained from bending tests on similar specimens having end-grain cores from 1 to 4 in. thick. One set

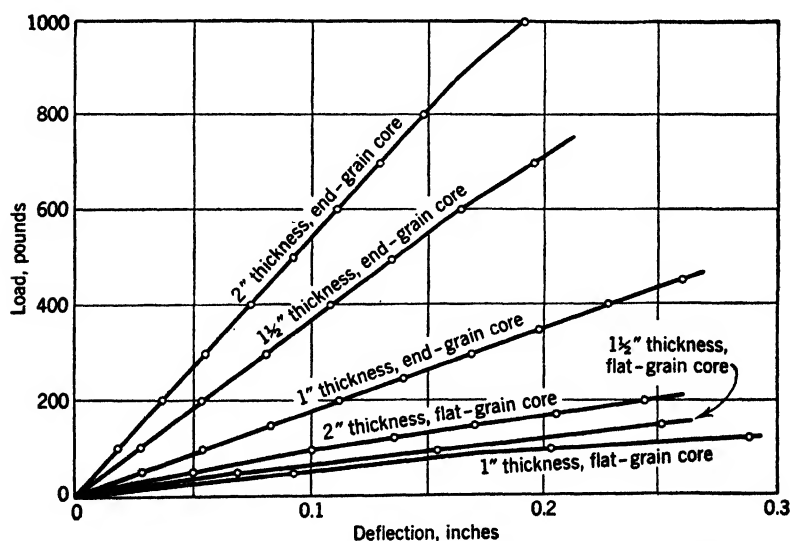


FIG. 18-15. Bending Tests on Sandwich Constructions Having 26-gage Steel (P.G.) Faces and Insulating Board Cores of Both Flat and End-Grain Construction.

of specimens had a reinforcing piece of pine ¾ in. wide in each slab, and one set had no wood members.



TABLE 18-18. BENDING STRENGTH OF INSULATED-STEEL SANDWICH-TYPE PANELS WITH AND WITHOUT ONE  $\frac{3}{4}$ -IN. WOOD REINFORCING MEMBER PER SPECIMEN

Width of Specimens: 5 in.

Span: 28 in.

Tested as Simple Beam

Metal Faces, EZB	Core, End Grain Insulation Board (Celotex), in.	Wood Member	Maximum Load, lb	Stiffness, Load per 0.1-in. Deflection, lb	Stiffness Factor <i>EI</i> for 5-in. Width
30-gage	4	No	1,680	1,075	4,920,000
30-gage	4	Yes	3,545	1,540	7,070,000
30-gage	3	No	1,370	925	4,240,000
30-gage	3	Yes	2,360	1,210	5,670,000
30-gage	2	No	945	610	2,790,000
30-gage	2	Yes	1,690	745	3,401,000
24-gage	3	Yes	3,485	1,705	7,850,000
24-gage	3	No	2,600	1,300	5,950,000
24-gage	2	Yes	2,425	1,090	5,000,000
24-gage	2	No	1,840	770	3,530,000
34-gage	3	No	1,095	850	3,890,000
34-gage	2	No	700	480	2,190,000
34-gage	1½	No	535	335	1,535,000
34-gage	1	No	321	157	716,000

## END-GRAIN SLABS AS ROOF DECKING

In view of the great strength of insulated-steel sandwiches having end-grain insulation-board cores, their use for roof decking in place of 2 in. planking plus insulation was also given consideration in the Elmendorf Corporation laboratory, and the properties of the material were compared with those of wood decking. It may be noted from Table 18-19 that the stiffness factors for steel-faced end-grain-core sandwich-type constructions 2 in. thick are of the same order as those of nominal 2-in. wood planking.

TABLE 18-19. COMPARISON OF *EI* VALUES FOR INSULATED-STEEL SANDWICH-TYPE CONSTRUCTIONS HAVING END-GRAIN INSULATION-BOARD (CELOTEX) CORES AND COMPUTED VALUES FOR NOMINAL 2-IN. (1½-IN.) WOOD PLANKING

Construction	<i>EI</i> for 12-in. Width
2" ponderosa pine planking	5,350,000
2" short-leaf yellow pine planking	7,520,000
2" long-leaf yellow pine planking	8,480,000
24-gage steel (EZB) faces, 2" end-grain core	8,480,000
24-gage steel (EZB) faces, 3" end-grain core	14,300,000
30-gage steel (EZB) faces, 2" end-grain core	6,700,000
30-gage steel (EZB) faces, 2" end-grain core containing $\frac{3}{4}$ " wood member 5" on center	8,170,000
30-gage steel (EZB) faces, 3" end-grain core	10,150,000
30-gage steel (EZB) faces, 3" end-grain core containing $\frac{3}{4}$ " wood member 5" on center	13,600,000

Sandwiches with end-grain cores and steel faces have several advantages over wood decking plus insulation. They are fire-resistant, and, being sheathed in metal, they cannot absorb moisture. The insulated-steel sandwich should, accordingly, be satisfactory as roof decking in industrial buildings, such as laundries and textile mills where the decking is exposed to high atmospheric humidities. As the metal used does not readily corrode in the weather, it should be possible to use this sandwich on pitched roofs without the usual built-up roofing over it. The metal surface takes paint so that the insulated-steel sandwich can be used to replace the conventional wood decking plus insulation and built-up roofing.

For the decks of industrial buildings, stiffness is one of the leading physical properties desired, because minimum deflection for a given roof load is important. Or put in another way, of two materials, other things being equal, that one is preferred which permits the greatest spacing of the supporting purlins. It is common practice to accept that spacing which when used will not cause the roof deck to deflect more than  $\frac{1}{250}$  of the span when it is loaded with the maximum distributed load that it may be called on in practice to carry. If the *EI* factors are known for each panel, it is a simple matter to compute the safe concentrated center loads and distributed loads for spans ranging from 48 to 96 in. The results of such computations are found in Table 18-20. It may be seen from this table that 2-in. slabs made with 30-gage steel faces will support a uniformly distributed load of 42 psf over a span of 84 in., and the same thickness will carry a load of 43 psf over a 90-in. span, when 24-gage steel faces are used. The same table shows that steel-faced insulation board (Celo-Steel) 3 in. thick made with 30-gage steel will safely carry a load of 42 psf over a span of 96 in., and the 3-in. thickness made with 24-gage facing will safely carry a uniformly distributed load of 60 psf on a span of 96 in.

Table 18-21 shows that the maximum load is four to six times the safe load as determined by a deflection of  $\frac{1}{250}$  the span, when the spans are 7 to 8 ft.

#### INSULATED-STEEL SLABS FOR HOUSES

Insulated-steel slabs with end-grain cores in 2-in. thickness may be used for walls with the complete elimination of vertical framing. This material therefore lends itself to prefabricated house construction. The wall slabs can be furnished to the job site in one standard width of various lengths. Window panels complete with the windows in place

TABLE 18-20. SAFE LOADS FOR INSULATED-STEEL SANDWICHES WITH END-GRAIN CELOTEX CORES TO BE USED AS ROOF DECKING

Span, $L$	Deflec- tion, $y$	Thickness of Sand- wich 2 in. 30-Gage Steel Faces $EI = 6,700,000$			Thickness of Sand- wich 3 in. 30-Gage Steel Faces $EI = 10,150,000$			Thickness of Sand- wich 2 in. 24-Gage Steel Faces $EI = 8,480,000$			Thickness of Sand- wich 3 in. 24-Gage Steel Faces $EI = 14,300,000$		
		$W$	$w$	$P$	$W$	$w$	$P$	$W$	$w$	$P$	$W$	$w$	$P$
48	0.192	895	225	560	1365	340	850	1130	285	710	1910	480	1195
60	0.240	570	115	355	865	175	540	725	145	450	1220	245	760
72	0.288	400	66	250	605	100	375	505	84	315	850	140	530
78	0.312	340	52	210	510	79	320	430	66	265	720	110	450
84	0.336	290	42	185	440	64	280	370	53	230	625	90	390
90	0.360	255	34	160	385	52	240	320	43	200	545	73	340
96	0.384	225	28	140	340	42	215	285	35	175	480	60	300

$W$  = total load on panel 12 in. wide in lb, uniformly distributed  $W = \frac{384 yEI}{5 L^3}$

$w$  = unit load in psf

$P$  = center load in lb on panels 12 in. wide

$$P = \frac{48yEI}{L^3}$$

$EI$  = determined by test

$y$  = deflection in in. and equal to  $\frac{1}{250}$  span

$L$  = length of span in in.

TABLE 18-21. INSULATED-STEEL SANDWICH-TYPE DECKING COMPUTED LOADS AT FAILURE FOR VARIOUS SPANS

Width of Panel: 12 in.

Span, <i>L</i> In.	Thickness of Sand- wich 2 in. 30-Gage Steel Faces			Thickness of Sand- wich 3 in. 30-Gage Steel Faces			Thickness of Sand- wich 2 in. 24-Gage Steel Faces			Thickness of Sand- wich 3 in. 24-Gage Steel Faces		
	<i>W</i>	<i>w</i>	<i>P</i>	<i>W</i>	<i>w</i>	<i>P</i>	<i>W</i>	<i>w</i>	<i>P</i>	<i>W</i>	<i>w</i>	<i>P</i>
48	2660	665	1330	3850	965	1925	5160	1290	2580	7300	1825	3650
60	2130	425	1065	3080	615	1540	4120	824	2060	5840	1170	2920
72	1780	295	890	2560	425	1280	3440	575	1720	4840	805	2420
78	1640	250	820	2370	365	1185	3170	490	1585	4480	690	2240
84	1520	215	760	2200	315	1100	2940	420	1470	4160	595	2080
90	1420	190	710	2050	275	1025	2750	365	1375	3890	520	1945
96	1330	165	665	1920	240	960	2580	325	1290	3650	455	1825

and door sections with the door set in a door frame can be furnished as units, and these can be joined to the adjacent wall sections in the same manner as that used for joining the standard wall panels together.

Low-pitched roofs can be made of this material with the complete elimination of roof rafters and a separate ceiling so that the panels

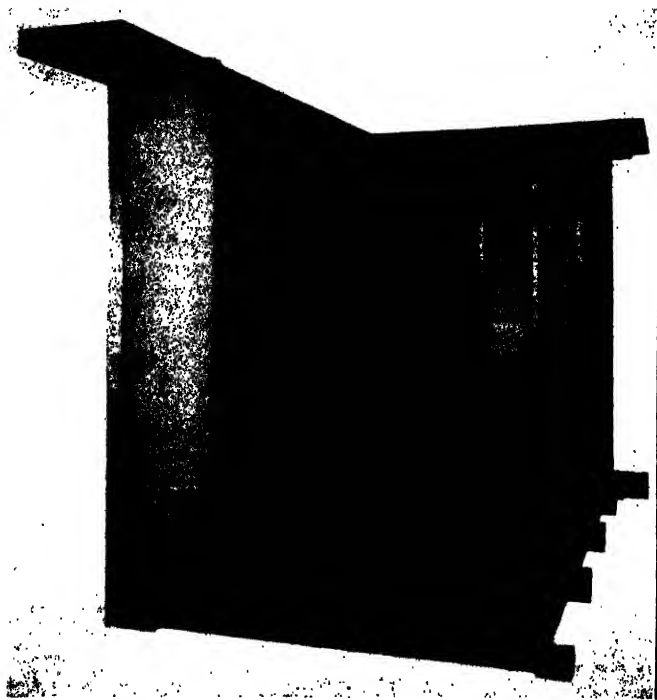


FIG. 18-16. Section of House in Which Wall, Roof and Floor Panels Are Insulated Steel Slabs with End-Grain Cores.

provide the structural strength required, the roofing, and the room ceiling all in one material. A partition of the same slab material can be used to support the roof at the ridge. Floors made of similar slabs can be placed on floor joists 4 to 6 ft apart. They provide the necessary strength with insulation and a smooth surface for floor coverings. The material solves the major problem of the ordinary steel house, namely, the elimination of metallic connection between the inside and the outside wall surfaces.

Figure 18-16 shows a section of a house erected in the Elmendorf Corporation laboratory embodying the features just described.

## METHOD OF MANUFACTURING

In the manufacture of the insulated-steel-faced sandwich the core is made first by laminating insulation board in the usual way to make slabs 4 or 5 in. thick, and then ripping these blocks into strips 2 or 3 in. wide, depending on the thickness of the insulated-steel panels desired. Five strips, 2 in. by 4 in. in cross section and 10 ft long, are placed side by side for the core of a panel, 2 in. thick, 20 in. wide, and 10 ft long.

TABLE 18-22. COMPARATIVE HOLDING POWER OF SCREWS AND NAILS IN WOOD AND IN METAL-FACED SANDWICHES HAVING END-GRAIN INSULATION BOARD (CELOTEX)

Load Applied Perpendicular to Face of Panel		Load per Screw or Nail, lb
Type of Screw or Nail	Applied to	
Sheet metal screw, $\frac{1}{2}$ " No. 5	Sandwich faced with 22-gage steel	349
Sheet metal screw, $\frac{1}{2}$ " No. 5	Sandwich faced with 26-gage steel	143
Sheet metal screw, $\frac{1}{2}$ " No. 5	Sandwich faced with 30-gage steel	97
Wood screw, $\frac{1}{2}$ " No. 5	Ponderosa pine plank	145
Wood screw, $\frac{3}{4}$ " No. 5	Ponderosa pine plank	249
3d nail, $1\frac{1}{2}$ " long	Ponderosa pine plank	98
3d nail, $1\frac{3}{4}$ " long	Ponderosa pine plank	111
2d nail, $1\frac{1}{2}$ " long	Ponderosa pine plank	72

A special adhesive is required to bond the metal faces to the end-grain insulation-board core, but any cold hydraulic press or hot-plate press of adequate size as used for the manufacture of plywood can be employed. Some of the adhesives which were found suitable set at room temperatures, whereas others require elevated temperatures.

TABLE 18-23. CLEAVAGE TESTS

Faces	Core, Insulation Board (Celotex), in.	Cleavage, lb		Ratio—End Grain to Flat Grain
		End Grain	Flat Grain	
$\frac{3}{16}$ " yellow pine	1	128	23	5.6
$\frac{3}{16}$ " yellow pine	$1\frac{1}{2}$	95	24	4.0
22-gage Galvaneal	$1\frac{1}{2}$	73	13	5.6

**Screw-Holding Power of Metal-Faced End-Grain-Core Slab Compared with That of Wood.** Table 18-22 shows the results of pulling tests to determine the holding power of screws in metal-faced end-grain slabs and of screws and nails in wood. It is noted that the holding power of screws decreases with the decreasing thickness of the metal faces used in the sandwich construction. A half-inch wood screw driven into ponderosa pine has about the same resistance to with-

drawal as a half-inch self-tapping screw of comparable gage driven into a sandwich slab having 26-gage steel faces.

TABLE 18-24. APPROXIMATE WEIGHTS OF INSULATED-STEEL (30-GAGE) SANDWICH

Thickness, in.	Weight, psf
1	2.6
1½	3.3
2	3.9
2½	4.6
3	5.3
3½	5.9
4	6.6

**Cleavage Strength of Flat-Grained and End-Grained Sandwich Constructions.** The relative resistance to peeling away of the faces from the core was determined by cleavage tests. Table 18-23 indicates that end-grain cores are about four to five times stronger than flat-grain cores in this property.

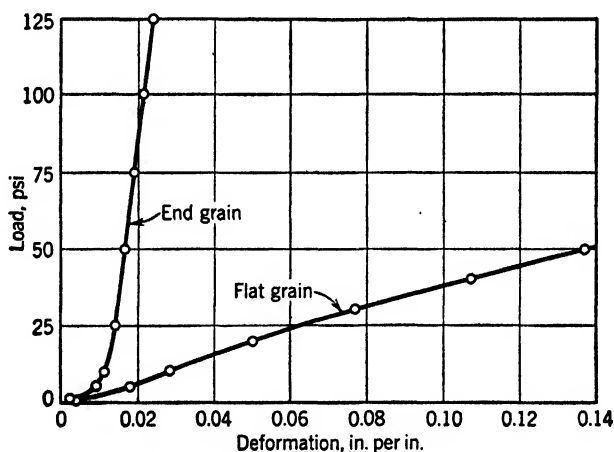


FIG. 18-17. Compression Tests on Insulating-Board Cores.

**Weight of Steel-Faced Sandwich.** Table 18-24 gives weight per square foot for various thicknesses of 30-gage steel-faced sandwiches. 30-gage sheet steel weighs 0.625 psf and insulation boards weigh 16 pcf.

**Thermal Conductivity of End-Grain Sandwiches.** It is a known fact that thermal conductivity is greater in the direction of the length of a fiber than across the fiber. The  $K$  factor for flat-grain cores is 0.34 Btu per hour per square foot per degree Fahrenheit per inch thickness and for end-grain cores is 0.75 Btu per hour per square foot per degree Fahrenheit per inch thickness.

**Compression Strength of Cores.** Figure 18-17 shows graphically the relative compressibilities of flat-grain and end-grain insulation-board (Celotex) cores. End-grain material is substantially stronger in compression. For example, at a pressure of 50 psi end-grain insulating board compresses only one-eighth as much as the flat-grain material.

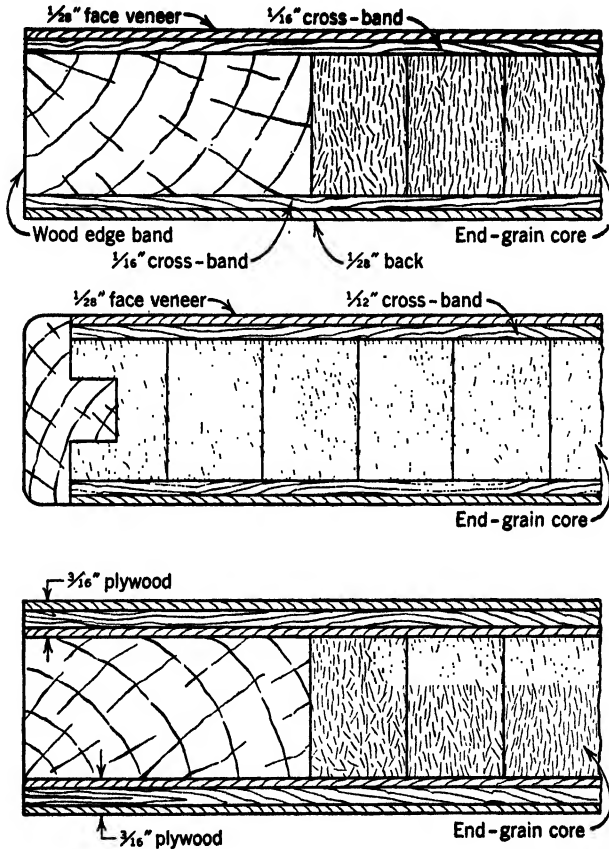


FIG. 18-18. Edge Constructions That May Be Used for Furniture Panels Employing End-Grain Insulating-Board Cores.

**Use of End-Grain Insulation Material in Furniture.** Attempts in the past to use ordinary flat-grain insulating-board cores for the manufacture of veneer-faced furniture panels in place of solid lumber cores have not been successful because of the low cleavage strength or resistance to splitting of the flat-grain material. Furthermore, when wood framing or banding was used along the edges of the panel, the



banding tended to show through the face. The core was also so soft that it could not withstand the pressures called for in veneering the faces.

Experiments conducted by various furniture factories in collaboration with the Elmendorf Corporation in the use of end-grain insulation board as the core of thick furniture panels, showed promising results. Such panels did not split in the core and withstood pressures of 100 to 125 psi without appreciable compression. Furniture panels made in this way are much lighter in weight and remain flatter than solid lumber-core panels.

Where the edges of the panels are exposed, as, for example, in desk tops, it is necessary to provide edge banding of wood. Figure 18-18 shows several types of edge construction that may be used for furniture panels using end-grain insulation-board cores.

## Plastic-Surfaced Plywoods and Their Properties

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Many millions of square feet of plastic-surfaced plywood, of both hardwood and softwood types, have been produced. These materials are essentially a specialized product of plywood manufacturers operating hot-plate plywood presses. Plastic-surfaced plywoods are produced by laying up multiple sheets of resin-impregnated paper with glue-spread wood veneers and curing both the plastic surfacing and the internal glue bonds of the plywood in a hot-plate press, usually in the same pressing operation.

### DESCRIPTION

The term—plastic-surfaced plywood—which is used to describe a relatively new class of material is somewhat general. The term “plastic” through common misuse has come to have very little meaning. Plastic-surfaced plywoods (Fig. 19-1), as manufactured for the last few years, consist essentially of plywood surfaced with paper impregnated with thermosetting resins, usually of the phenol-aldehyde type. Although the general term “plastic-surfaced plywood” might well include plywoods surfaced with a thermoplastic sheet material, a thermosetting resin-impregnated fabric, or merely a resin-base paint finish, in the following discussion the term is used to refer to plywoods surfaced with a cured phenol-aldehyde-impregnated paper, in which the surfacing paper is cured at the same time internal plywood glue lines are cured—not a composite laminate produced by first curing the plastic laminate and then gluing it to a plywood core in a separate operation.

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In further describing plastic-surfaced plywoods, it is obvious that the base plywood itself must be completely specified or described in order to define a given plywood from among the thousands of combinations possible. In addition, the precise nature of the plastic surface or overlay should be defined as to type of resin, resin content, color, thickness of plastic surface, and type of surface finish.

Since the resin-impregnated papers currently being used by the plywood industry to produce plastic-surfaced plywoods contain thermosetting resin, it is essential that the material be subjected to heat

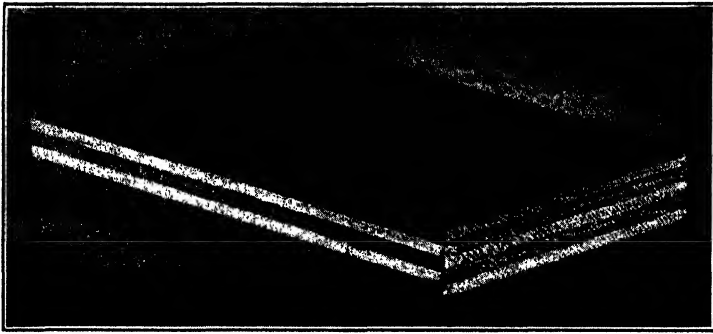


FIG. 19-1. Plastic-Surfaced Douglas Fir Plywood.

in order to cure the resin. As a matter of practical fact, since it is also necessary to have sufficient shelf life in the uncured resin-impregnated paper to permit the maintenance of operating stocks without spoilage caused by the resin setting up in the roll prior to use, it is necessary to apply heat appreciably greater than summer atmospheric temperatures for an appreciable interval of time in order to effect cure in the manufacturing operations. In order to facilitate resin flow, the use of pressure is necessary.

### MANUFACTURE

The plywood manufacturer lays up his glue-spread wood-veneer sandwich in much the same manner that he would for the production of ordinary plywood. Sheets of uncured resin-impregnated paper are placed on the outside of both face veneers, using the proper grade, number of sheets, color, and so on required for the specific application. The wood-veneer-impregnated paper assembly is then placed between sheet-metal cauls or press plates having the proper surface finish required for the given application, and the whole is loaded into the hot-

plate press. Heat and pressure are applied for a sufficient interval of time to flow and cure the resins contained in the surfacing paper and to cure the internal glue bonds between the wood veneers. No additional glue line need be applied to the outside surface of the face veneer since sufficient resin flows from the plastic surface to insure adequate bond of the plastic surface to the base plywood.

There are several variations of the so-called "one-step process" outlined in the preceding paragraph that have been used in the past but have been almost completely supplanted by the "one-step process." Although the process itself is quite simple in principle, the degree of both raw material and process control that must be exercised in order to insure satisfactory uniform product is relatively great when compared with that used in the production of ordinary grades of unsurfaced plywoods. Because relatively high temperatures must be used for appreciable intervals of time in order to cure the phenolic resins contained in the plastic surface, almost all grades of plastic-surfaced plywoods now being produced use phenolic resin adhesives to form the glue bonds between the wood veneers, thereby qualifying the base plywood as exterior, marine, or water-proof in grade. The lower-temperature plywood adhesives (including urea-formaldehyde adhesives) are almost without exception unsatisfactory for forming the wood-veneer glue bond owing to their breakdown at phenolic curing temperatures.

#### PROPERTIES

Since it is a composite material, the properties of plastic-surfaced plywood depend both on the nature of the base plywood (number and thickness of wood veneer, type of wood, defects in wood used, type of adhesive used, and so on) and on the nature of the plastic surfacing or overlay (type of base paper, type of resin, ratio of resin to paper, and the like). There are two general classifications of plastic-surfaced plywood being produced today based on resin contents of the plastic surface. The high-resin-content plastic surfaces contain approximately 40 to 50 per cent resin and when cured at normal plywood-manufacturing pressures of 200 to 250 psi attain a specific gravity of 1.35 to 1.40, a practical maximum specific gravity indicative of a well-flowed cured paper-base phenol-formaldehyde laminate. The other classification covers low-resin-content grades of resin-impregnated papers having resin contents ranging from approximately 20 to 40 per cent. In general, phenolic-resin-impregnated papers in this group do not possess sufficient flow when being cured to self-bond reliably to the face veneer of the plywood, nor do the low-resin-content grades attain

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specific gravity of 1.35 to 1.40 at normal plywood-pressing pressures. The lower-resin-content grades generally require painting in order to improve their weathering properties if they are to be used in exterior applications. There are no plywoods in commercial production at the present with resin-impregnated paper surfaces containing less than 20 per cent resin. Surfaces containing less than 20 per cent resin approach the properties of unimpregnated paper rather than those of a thermosetting paper-base laminate.

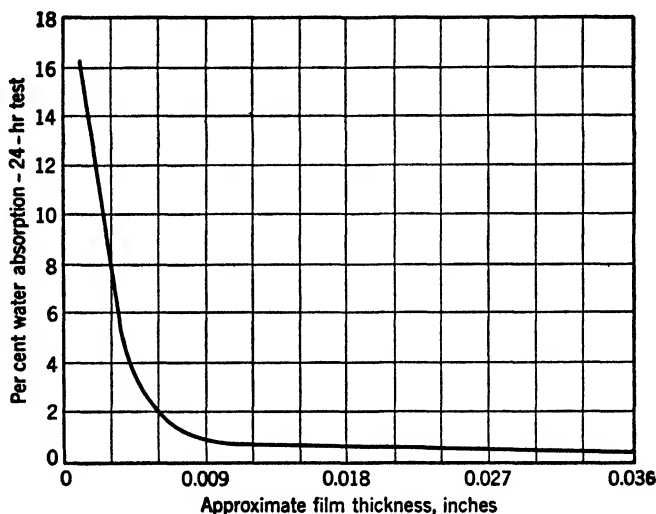


FIG. 19-2. Influence of Film Thickness on Water Absorption. Curve typical of 50 per cent resin surface film on  $\frac{1}{4}$ -in. 3-ply Douglas fir plywood.

**Moisture.** Plastic-surfaced plywoods possess a low rate of water absorption (Figs. 19-2 and 19-3) compared with unsurfaced exterior-grade plywood. This is particularly true in the case of high resin grades. Although the rate of water absorption of plastic-surfaced plywoods is substantially lower than regular plywood, it should be appreciated that, under a condition involving a continued immersion in water, the plastic-surfaced material ultimately reaches essentially the same equilibrium moisture content as the unsurfaced plywoods.

As a corollary of the low rate of water absorption, plastic-surfaced plywood also has a low rate of water-vapor permeability. Although the plastic surface by no means constitutes an absolute vapor barrier, it does serve as a good vapor barrier for construction work where vapor barrier is desired. As with all vapor barrier on construction work,

joints must be sealed properly in order to make the barrier effective. It should be appreciated that the type of phenol-aldehyde resin used to impregnate the paper for plywood surfacing can materially influence some of the physical properties of the surface. For example, water-soluble-phenol aldehyde resins have appreciably smaller molecular size than alcohol-soluble phenol-aldehyde resins and, therefore, tend to penetrate both the sheet of paper and the cellulose fiber itself more thoroughly than alcohol-soluble resins. Plastic-surfaced plywood produced from paper impregnated with water-soluble phenolic resin will have lower moisture-absorption properties and water-vapor permeabil-

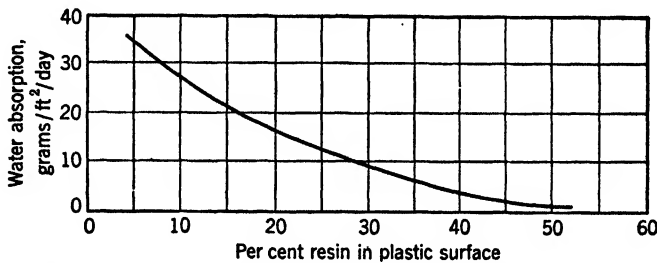


FIG. 19-3. Water Absorption versus Resin Content. Curve typical of surface film 0.009 in. thick on  $\frac{1}{4}$ -in. 3-ply Douglas fir plywood.

ity than plywood surfaced with paper impregnated with an equal percentage of alcohol-soluble resin.

**Abrasion.** The high-resin-content plastic surfaces have good abrasion resistance, both wet and dry, although not so good as that produced with melamine-aldehyde-impregnated papers commonly used as the surface material on decorative laminates. The low-resin-content plastic surfaces do not have the same degree of abrasion resistance as the high-resin-content surfaces but still offer a surface much more abrasion-resistant than ordinary plywoods. It should be appreciated that ultimate wear resistance of the material is a function of both abrasion resistance and thickness of material and that plastic surfaces normally furnished on plywood seldom exceed 0.050 in. thick.

**Weathering.** Accelerated weatherometer tests performed on unpainted high-resin plastic-surfaced plywoods indicate that the material possesses good weathering properties; however, it is difficult to translate the results obtained in such accelerated tests into precise terms of actual atmospheric weathering. Accumulation of actual weathering data is time-consuming, and, although samples have been exposed on several weathering racks in various parts of the United States for as

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long as 4 years, this is obviously too short an interval of time on which to base an estimate of ultimate weathering properties.

Since the grades of plastic-surfaced plywoods currently being produced commercially contain phenolic resins, these materials are subject to the typical yellowing of phenolic resins when exposed to ultraviolet light for prolonged intervals. In darker-colored plastic surfaces this yellowing is not apparent, since it is concealed by the dark base color. Properly processed plastic-surfaced Douglas fir plywoods will not surface-check and have markedly less tendency to grain-raise under varying atmospheric conditions. The low-resin-content grades of plastic-surfaced plywood should be painted when destined for exterior applications in order to provide a good weathering surface.

**Insects and Decay.** Plastic-surfaced plywoods having a high-resin-content surface film are proof against the action of termites and marine borers when the edges of the panels are properly sealed. They also resist attacks by fungus growth.

**Fire and Chemical Resistance.** No exhaustive tests have been conducted to determine the relative combustibility of plastic-surfaced plywood. However, on the basis of limited tests, it appears that phenolic resin plastic-surfaced plywoods have a lower rate of flame spread than ordinary plywood.

The chemical resistance of plastic-surfaced plywood is essentially the same as that of phenolic paper-base laminates. As such, it is unaffected by weak inorganic and organic acids and alkalis. Its alkali resistance is not so good as its acid resistance. It is not affected by common organic solvents such as ketones; acetones; esters; hydrocarbons; and animal, vegetable, or mineral oils. It has good resistance to the action of saline solutions, and the surface is not affected by prolonged exposure to sea water.

**Finishes.** Plastic-surfaced plywoods are available in a range of surface finishes and colors. The range of colors for phenolic-base surfaces, with one or two exceptions, is limited to darker colors such as black, brown, maroon, and green, where the effect of the yellowing of the phenolic resin under prolonged exposure to ultraviolet light is concealed by the base color. Melamine- and urea-formaldehyde resin-impregnated papers, although capable of producing laminates that are light in hue and light-stable, are not suitable for direct application to softwood plywoods in the plywood pressing operation. It may well be that the commercial production of light-colored plastic-surfaced plywoods will be accomplished with papers impregnated with contact-pressure resins.

The type of surface finish obtained with a given grade of high-resin phenolic-impregnated paper is for the most part determined by the finish of the sheet-metal caul or press plate against which the material is cured. A highly polished chromium-plated caul will yield a glossy

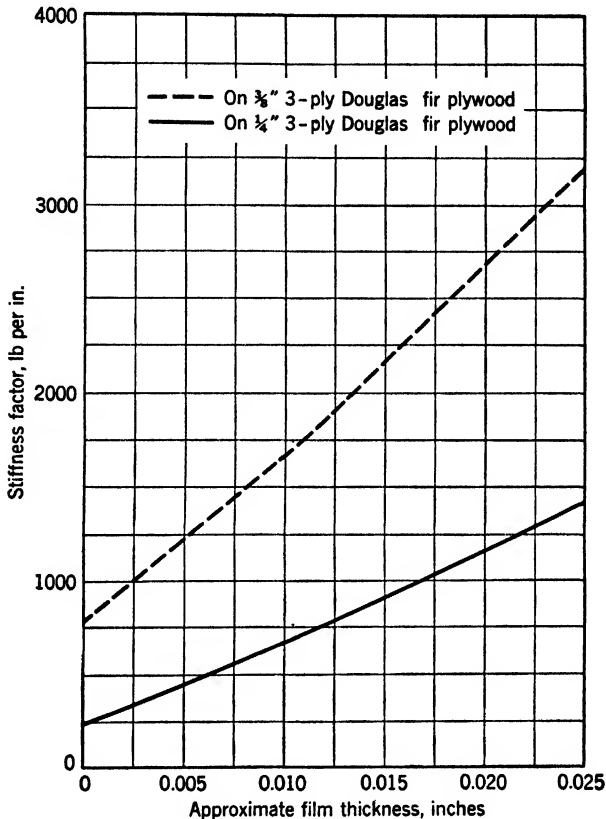


FIG. 19-4. Influence of Film Thickness on Stiffness Factor ( $EI$ ) Transverse, or Perpendicular to Grain Direction of Face Veneers. Curves typical of 50 per cent resin surface films applied with grain of paper parallel to grain of face veneers.

plastic surface; a brushed caul plate such as the standard No. 2B finish obtainable on stainless steel will yield a satin-like plastic finish; a relatively new galvanized iron caul reproduces the typically crystalline galvanized pattern. A sandblasted caul will yield a rough plastic surface having a high coefficient of friction. Another means of producing a rough antiskid plastic surface is to make use of wire screening between the metal caul and the plastic during the curing operation.



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Most of the plastic-surfaced plywoods produced to date have been pressed against galvanized iron cauls and, therefore, have surface appearances ranging from the crystalline pattern to a dull semigloss, depending on the extent to which the zinc galvanizing has been worn by repeated pressing operations. When a glossy surface is desired from such panels, a refinishing operation is necessary.

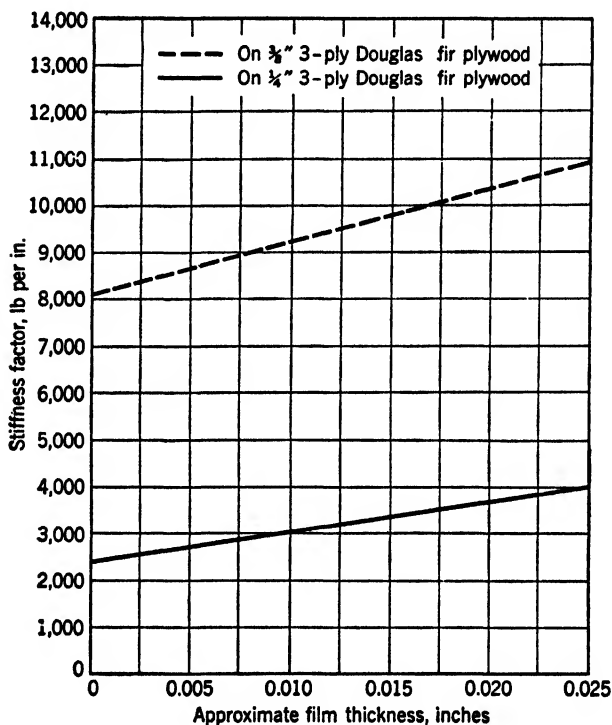


FIG. 19-5. Influence of Film Thickness on Stiffness Factor ( $EI$ ) Parallel to Grain Direction of Face Veneers. Curves typical of 50 per cent resin surface films applied with grain of paper parallel to grain of face veneers.

The lower-resin-content grades, because they do not exhibit complete flow in the pressing operation, generally have a dull matte finish particularly well fitted to receive the paint coats that are necessary if such low-resin grades are to be used in exterior applications.

**Mechanical and Physical Properties.** Relatively few data based on actual tests have been accumulated on the strength properties of plastic-surfaced plywood. Tests that have been conducted on the material present only a fragmentary picture of the strength properties of the

thousands of possible combinations of phenolic paper-base plastic surfaces with various types and thicknesses of wood-veneer cores. However, sufficient tests have been made to confirm the fact that strength properties calculated in accordance with both empirical and theoretical formulas for wood-veneer sandwich materials, such as plywood, yield results in substantial agreement with actual strength properties in the case of plastic-surfaced plywoods.

TABLE 19-1. TYPICAL PHYSICAL PROPERTIES OF 50 PER CENT PHENOLIC RESIN PAPER-BASE LAMINATES

	Parallel-Laminated	
	With Grain	Cross Grain
Specific gravity	1.39	1.39
Tensile strength, psi	18,000	14,000
Elastic modulus (tension) psi	$1.60 \times 10^6$	$1.15 \times 10^6$
Compressive strength, psi		
Flatwise	32,800	32,800
Edgewise	21,900	20,100
Flexural strength, psi		
Flatwise	17,200	15,200
Edgewise	18,100	14,700
Flexural modulus, psi		
Flatwise	$1.44 \times 10^6$	$1.07 \times 10^6$
Edgewise	$1.43 \times 10^6$	$1.04 \times 10^6$
Shear strength (Johnson Tool), psi		
Flatwise	12,000	12,000
Edgewise	12,000	12,000
Impact strength (Izod, notched), ft-lb per in. of notch		
Flatwise	2.56	1.56
Edgewise	0.58	0.56
Hardness (Rockwell, scale M)		
Flatwise	127.4	127.4
Edgewise	125.7	125.7

In order to calculate the strength properties of various combinations of plastic-surfaced plywood, it is first necessary to know the strength properties of the cured plastic surface or overlay itself which in practice are determined on a laminate molded from the surfacing material alone, without wood veneers. In preparing such laminates molding conditions should approximate, with reference to time, temperature, and pressure, the conditions under which the material is molded to the base plywood in actual production. Methods for calculating the strength properties of various plywood and wood-veneer assemblies are outlined in the literature. The strength properties of various types of resin laminates are also available in the literature. Table 19-1

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lists typical strength values for phenolic-resin-impregnated paper laminates currently most widely used in the production of plastic-surfaced Douglas fir plywood. These values are typical of a high-resin-content product containing approximately 50 per cent resin.

The strength improvement afforded by a relatively thin skin of plastic (for example, 0.010 in. thick) on plywood is probably too small to utilize in most design work. However, as the thickness of the plastic surface is increased, the influence of the plastic on the flexural strength, particularly in the direction transverse to the grain of the face veneers, and on other properties related to flexural strength becomes appreciable (Figs. 19-4 and 19-5).

### FABRICATION

The methods of fabricating plastic-surfaced plywoods should take into account the fact that the material is both a plywood product and a thermosetting laminated product.

In sawing plastic-surfaced plywoods, particularly the high-resin-content grades, it is important to handle the material so that chipping of the plastic surface at the bottom surface of the saw cut is eliminated. Standard wood saws may be used, but best results are obtained by using high-speed power saws with little or no set and with as much lead as possible to the teeth. When circular saws are used, the diameter of the saw should be large, preferably 10 in. or larger, and the piece to be sawed should be fed slowly with the table adjusted so that the saw extends through the piece only about  $\frac{1}{4}$  to  $\frac{1}{2}$  in. Since it is important to have a sharp saw for best results, the use of tungsten carbide saws will minimize sharpening where much sawing is contemplated. Although the use of power saws is preferable, hand sawing may be done, providing sharp fine-toothed saws without much set are used.

The edge sealing of plastic-surfaced plywoods should be done with the same techniques and materials used for edge-sealing ordinary plywood panels to meet the requirements of the particular service condition.

The painting of the lower-resin-content grades of plastic-surfaced plywoods presents no problems, and virtually any paint that will adhere to wood may be used. However, if it is desired to paint the high-resin-content grades of plastic-surfaced plywoods, some attention must be given to the type of paint used. Paints of the air-drying type may be applied to high-resin-content plastic-surfaced plywoods by spraying, brushing, or dipping. Since the high-resin-content types of plastic-surfaced plywoods provide an almost impervious membrane, paint re-

quires a somewhat longer drying time, compared to the same paint on a wood surface. For the same reason no sealer coat is necessary.

In painting high-resin-content plastic-surfaced plywood, the specific requirements of the job will dictate whether a glossy or flat paint is to be used. Medium-to-long-oil, 100 per cent alkyd-base paints or phenolic-base paints and varnishes will provide satisfactory adhesion to the plastic surface. Although most production of plastic-surfaced plywoods makes no use of caul-plate lubricants, if any difficulty is encountered in obtaining adhesion with these types of paints, the surface should be wiped with naphtha or other organic solvents to remove residual lubricants that may be present.

Phenolic paper-base plastic-surfaced plywoods may be bonded to themselves at room temperatures with adhesives of the resorcinol-formaldehyde, phenol-formaldehyde, or urea-formaldehyde types where the manufacturer has specifically recommended their use at room temperatures. The adhesive manufacturer's instructions should be followed in mixing, because of variations in the pot life of the mixed adhesives, the permissible open assembly time, and the length of time joints should be kept under pressure. In general, the joints should be placed under the highest pressure attainable, with attention to the manufacturer's recommendation concerning minimum pressure. When the plastic surface is glued to another plastic surface, a minimum spread of adhesives should be used. Maximum bonding strength will be obtained if a highly glazed plastic surface is lightly sanded with fine sandpaper before the adhesive is spread.

Where equipment is available for the maintenance of heat while the glue joint is under pressure, heat-setting resin adhesives may be used to develop high bond strength. Plastic-surfaced plywoods may be bonded to themselves, to wood, metal, or glass with rubber-base cements. Although these cements do not make so strong a bond as the resin adhesives, they are convenient to use and provide a flexible joint should this be desired.

## Structural-Sandwich Construction

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### INTRODUCTION

It is reported that the fourth Earl of Sandwich had food brought to him in the form of meat between slices of bread while he was playing cards so that he might be able to play without stopping. This combination has of course become well known as the sandwich. The meaning of the word sandwich has been broadened to cover many things, however. The dictionary defines the sandwich as "two thin slices of bread, having between them meat, cheese, or other savory foods; hence, any combination of alternating dissimilar things, especially a trio of objects of which the one in the middle is different from the others." The latter definition is obviously very broad and is too general for the purposes of this discussion. With the object of restricting the subject, a sandwich, or, preferably, sandwich construction, will be defined arbitrarily as consisting of two faces of relatively thin high-strength high-density material bonded to a core of relatively thick low-density material, where the functions of the latter are primarily to stabilize mechanically the thin faces and to provide a high stiffness factor for the combination by means of separation of the faces. It must be noted that the word "bonded" included in this definition is essential and is not just an added attraction, as is the analagous buttering of the bread of the original sandwich.

By mechanical stabilization of the faces is meant that the core material supports the faces to enable them to be stressed to or near their yield or ultimate strengths in compression or shear or combined stresses without buckling before the sandwich construction fails. This is, of course, desired in order to utilize the structural materials of the faces

to the fullest extent possible for the least expenditure of weight. This stabilization idea is not new, as Gough<sup>2</sup> has pointed out. As early as 1849 the idea was used by William Fairbairn when carrying out experiments for bridge design. However, activity in the field of sandwich construction as defined has been most extensive in the last 5 or 10 years and has resulted in the application of structural sandwich construction in aircraft, housing, boats, truck bodies, and so on.

#### TYPES OF CORE MATERIALS \*

The faces of sandwich construction may be metal, plastic, wood, or other structural materials. The properties of these materials, in general, are not discussed in detail here, because data on them are available from many sources and are relatively well known. However, this is not true of low-density core materials, and, since the properties of the latter as well as those of the faces are of essential interest in sandwich construction, some of the characteristics of these materials are reviewed here.

Low-density core materials have been made from the following:

- (a) Cellular plastic materials, thermoplastic and thermosetting.
- (b) Cellular synthetic or natural rubber.
- (c) Expanded wood or other fibers, with or without resin binder.
- (d) Natural low-density woods.
- (e) Mechanically constructed cells employing relatively high-density material as cell walls.
- (f) Expanded inorganic materials, as glass.
- (g) Miscellaneous.

Some specific examples of these materials that have been made into or occur naturally as low-density cellular materials are:

Cellulose acetate.

Polystyrene.

Polymethyl methacrylate.

Polyvinyl acetate.

Polyvinyl formal.

Polyvinyl chloride.

Polyethylene.

Shellac.

Phenol formaldehyde.

Urea formaldehyde.

Polyesters, such as alkyd-styrene copolymers and polyurethanes.

\* See Chapter 22 for further discussion of cores and of methods of making sandwich materials.

Butadiene-acrylonitrile copolymers.

Butadiene-styrene copolymers.

Natural rubber.

Chlorinated natural rubber.

Cyclicized natural rubber.

Cyclicized synthetic rubbers.

Zein and other proteins.

Calcium alginate.

Cork.

Wood fiberboard.

Balsa and quipo.

Foamed glass.

Honeycomb, latticework, or other cellular construction from paper, cotton, or glass-fabric-base plastic, metal, plywood, wood, and vulcanized fiber.

This list, of course, does not exhaust the possibilities but represents materials which have actually been made, at least experimentally, in the form of cellular low-density materials. The term "low density" has not been specifically defined, but the densities of principal interest are generally within the approximate range of 4 to 25 pcf.

Many of the methods for producing cellular materials have been outlined by Sachs.<sup>51</sup> These and others are reviewed in this chapter. Thermosetting plastics like phenol and urea formaldehyde polymerize by condensation, splitting off molecules of water. If the reactants are heated with a catalyst, the water can be vaporized to steam and serves as a blowing agent to expand the material into cellular form before the material hardens. This expansion may also be obtained by the water acting on some added ingredients, such as calcium carbide, in which case acetylene gas is produced. These resins may also be expanded and cured at elevated or room temperatures (depending on the resin and catalyst), by incorporation of a suitable catalyst, emulsifying agent or foaming agent, and stabilizing agent into a solution of the resin. The latter can be beaten or whipped into a foam, and the resin is set and dried. A foam-stabilizing agent is necessary to prevent settling out before the resin is cured.

The polyester thermosetting resins which cure by addition polymerization only may be made into cellular materials and cured at elevated or room temperature similar to the last procedure described, except that no solution is used since the resins are available as liquids in monomeric or partially polymerized form. Lincoln <sup>48</sup> has described the use of such a foam.

The phenolic, urea, and polyester thermosetting-resin cellular materials, if of sufficient strength and stiffness to be of interest, are gen-

erally relatively brittle and somewhat crumbly materials. This does not prevent their use in some applications, however. The cellular structures formed from these thermosetting materials vary in cell size, degree of interconnection of cells, uniformity of cell size, and so on, depending on the particular techniques and materials used. This statement is also true, of course, for any of the other cellular materials. However, in general, average-unit cell sizes as small and as uniform as those of some of the thermoplastic materials have not been obtained with the thermosetting plastics.

Since the thermosetting cellular plastics are ordinarily difficult to form, it is usually convenient to cast or expand them into the desired form when they are made. This is shown by Lincoln.<sup>43</sup> It should also be noted that, in common with most other cellular plastic and rubber materials, these cellular materials are produced with a "skin" or surface layer of unexpanded material, which may be very thin, as 0.001 or 0.002 in., or it may be thick, with a gradual density gradient into the body of the material. This again depends on the materials and techniques used. This surface may have to be removed in order to obtain a good bond in gluing to the material or in order to obtain a material of uniform density. Cellular-plastic materials of the thermosetting type have been made in densities of about 1 pcf and up.

Thermoplastic materials may be expanded by the incorporation of gas-producing chemicals, such as sodium bicarbonate which produces carbon dioxide or certain diazo compounds which decompose to yield nitrogen. The chemicals used must be uniformly distributed in the material by thorough mixing while the plastic is in a softened condition. The material may then be subjected to heat and pressure in a mold to plasticize the material and decompose the expansion agent. On controlled release of the pressure, the gas which has been produced expands, forming the cellular structure. The material is cooled before removal from the mold.

Some of the variables affecting the density and cell size produced are the type, amount, and particle size of the expansion agent; temperature and pressure; amount of expansion allowed, as controlled by separation of plates, and so on. Thermoplastics may also be expanded with gas-producing chemicals in an extruder and extruded into continuous strips of cellular material.

Solvents may be used instead of gas-forming chemicals in the expansion of thermoplastic materials using compression molding or extrusion. A relatively small amount of solvent, which may be non-polymerizable, as benzene, or polymerizable, as a monomeric liquid



such as an acrylate, is incorporated in the material. After heating under pressure, release of the pressure causes vaporization of the solvent, since the latter is above its boiling point, and the material is blown into cellular form.

Another procedure for expansion of thermoplastic materials is the high-pressure gas process. A gas such as nitrogen is dissolved in liquid partially polymerized resin under high pressure, as 3000 psi, and, as the resin is polymerized and hardened by heating followed by cooling, the pressure is released, the gas coming out of solution and forming the cellular structure. The hardening of the material and release of gas must be carefully co-ordinated since the latter must not occur when the material is too soft or too hard. Plastic material already polymerized may be softened by heat or by a solvent, subjected to a gas under pressure and expansion obtained by releasing the pressure.

Low-density materials have also been prepared from thermoplastic fibers such as polystyrene. Fibers in the form of bats having a very low apparent specific gravity and containing a small percentage of solvent are consolidated by molding under heat and pressure, the density obtained depending on the molding conditions.

It should be noted that the heat-distortion points of the thermoplastic low-density materials are lowered by the presence of solvents in the finished material. Therefore, unless the amount present is not objectionable, the solvents usually must be removed by drying. This may be a long and difficult process where the cells are not interconnecting.

Cellular low-density materials have also been prepared from mixtures of thermosetting and thermoplastic materials. An example is a polymerized stable gelled form of an aqueous emulsion containing a water-soluble urea-formaldehyde resin, polyvinyl acetate, and polymethyl acrylate.

Although the expanded synthetic and natural rubbers could be classified under the thermoplastic and thermosetting plastic materials, they have been listed separately. These materials are produced generally either by a high-pressure gas or by chemicals. When the material is thermosetting and is vulcanized to a hard state, the expansion by high-pressure gas technique must be timed correctly during the curing. Cellular thermosetting hard synthetic rubbers, such as butadiene-acrylonitrile copolymer base, may be produced with incorporation of gas-forming chemicals by one- or two-stage processes. For either, all ingredients are first milled and sheeted, and rectangular pieces are cut out, of weight, width, length, and thickness depending on size of molds to be used and density desired. In the one-stage process, the material

is placed in a closed mold and heated, being expanded and cured to a hard board of the desired density. In the two-stage process, the sheeted material is placed in a closed mold of essentially the same size as the sheet and heated under pressure to effect a partial cure and to decompose partially the expansion agent. The pressure is then suddenly released and the sheet is ejected, expanding in three dimensions to a larger cellular rectangular sheet, still soft and rubbery. The latter is then placed in a closed mold and is heated under pressure. Some additional expansion occurs, and a hard cellular board is formed by completion of the curing. The material can be made to be stable for some time in the partially cured and expanded rubbery state, so that it may be supplied in this form to fabricators. These can use the material to expand and cure it in place between two sandwich faces, which is of some advantage in particular cases.

Low-density fiberboards may be made by felting wood or other fibers, with or without added synthetic resin, or by adding fibers to a foamed synthetic resin. Fibers may be obtained from steam-expanded wood chips, wood-paper pulps, or other sources.

TABLE 20-1. EFFECT OF ADDITION OF FINE-CHOPPED GLASS FIBERS TO EXTRUDED CELLULAR CELLULOSE ACETATE

	Unfilled	Filled with About 3% by Weight of Glass Fiber
Density, pcf	6.3	6.5
Tensile strength, flatwise, psi	103	350
Ultimate compressive strength, flatwise, psi	107	160
Compressive stress at 2%, compressive flatwise, psi	89	150

Addition of fibers to a low-density cellular material may or may not increase the mechanical properties of the latter. For example, addition of up to 15 per cent of cellulose fibers (from wood pulp) to calcium alginate foam results in properties lower than those of the original foam. On the other hand, addition of about 3 per cent of very fine-chopped glass fibers to extruded cellular cellulose acetate almost doubles the mechanical properties. Examination of the glass fibers in the finished material shows that they average about 3 microns in diameter and about 25 to 100 microns in length. The fibers are added before extrusion and expansion. No theoretical explanation is offered for either case. The glass fibers are so small that they cannot be seen in the 20 $\times$  photographs, Figs. 20-15 through 20-17, and the amount present is slight. Table 20-1 shows increases obtained in some of the properties.

Mechanically constructed equivalents of cellular plastics may be made in many ways. Probably the most generally used of these mechanical equivalents is one form or another of the type termed honeycomb because of the similarity in appearance to a cross section of a bee's honeycomb. Sheets of paper or thin glass or cotton fabric are impregnated with a thermosetting resin, and then corrugating and cur-

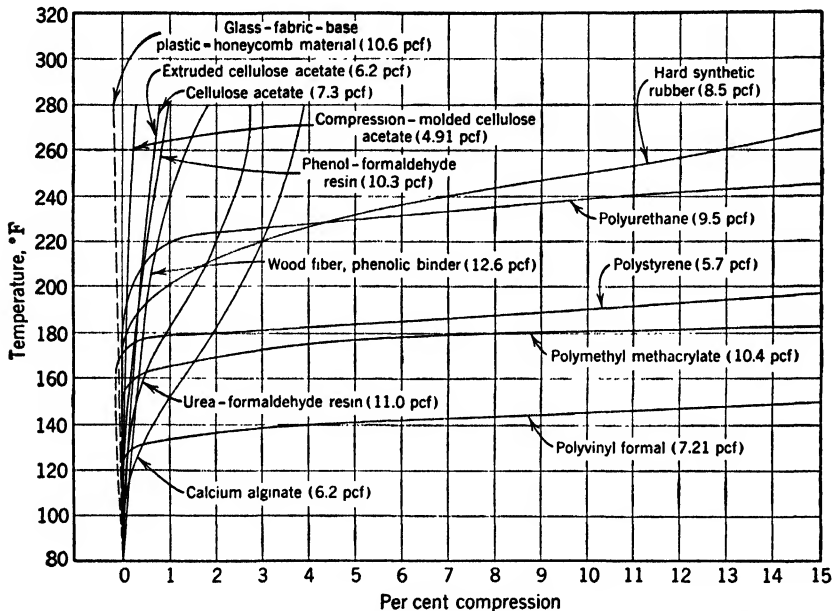


FIG. 20-1. Compressive Heat-Distortion Curves for Low-Density Core Materials. 15 psi compressive stress. Temperature raised 2°F per minute. All specimens loaded flatwise (in thickness direction).

ing of the resin are done simultaneously. Another procedure involves partially impregnating the paper or fabric to be used with a small percentage of thermosetting resin and curing before corrugating by passing through corrugating rolls, the stiffness and consistency of the material being such that the corrugations retain their shape while the material is afterwards further impregnated and laid up. In any case, a number of these corrugated sheets are stacked on each other to the desired thickness, care being taken to provide proper alignment of the cells formed by the indentations of the corrugations of two adjacent sheets. Where the material is already plastic-impregnated and cured, additional resin glue is used between layers to bond the corrugations

together. Where the material is partially impregnated, the corrugations are reimpregnated before stacking, then laid up together, and cured and bonded together simultaneously. In this manner blocks of

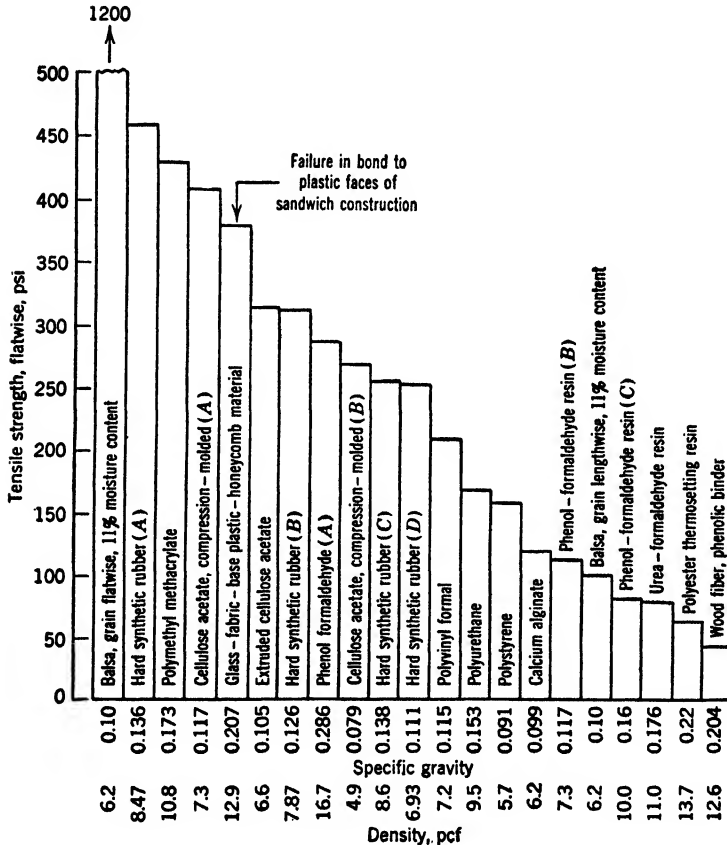


FIG. 20-2. Tensile Strength of Low-Density Core Materials. Tested in flatwise (thickness) direction.

honeycomb are obtained. To obtain core material of desired thickness, slices are sawed from the edges of these blocks.

An entirely different procedure is that in which narrow glue lines are applied, equally spaced at short intervals with respect to the width of the material, as paper, and running the full length of the material, to produce a striped effect. A large number of sheets of this glue-striped paper are stacked on each other with the glue stripes of adjacent sheets

offset by half the given interval. The stock is then heated under pressure, curing the glue, and gluing the sheets together at the various glue lines. The stock may then be pulled apart and expanded into a honey-

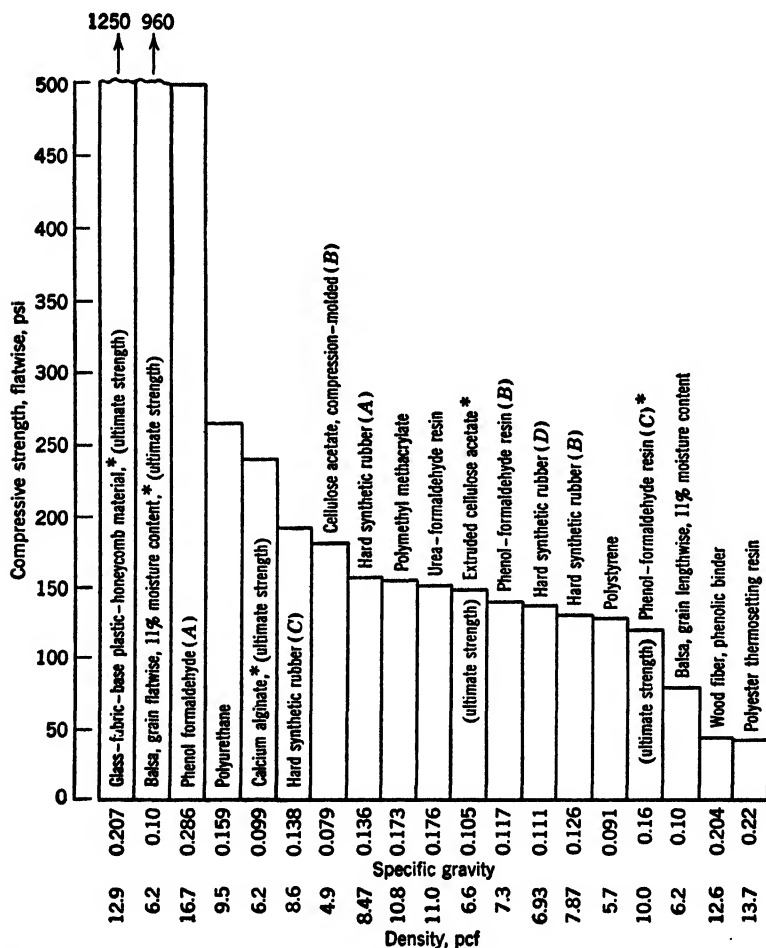


FIG. 20-3. Compressive Strength of Low-Density Core Materials. Tested in flatwise (thickness) direction. Stress at 2 per cent strain, unless marked with \* which represents ultimate strength.

comb. While being retained in this expanded position, the material is impregnated with a thermosetting resin by dipping. The resin is then cured, and a permanently rigid honeycomb block is obtained from which core material may be sliced. Descriptions and properties of

honeycomb-type cores are given in references 30, 38, 42, 44, 45, 53, 54, 60, 61, 65, 68, 69, 70, 73, 80, 86, 88, 89, 96, and 99.

There are many other mechanically constructed equivalents of cellular plastics. One is made by gluing lengths of paper base or other

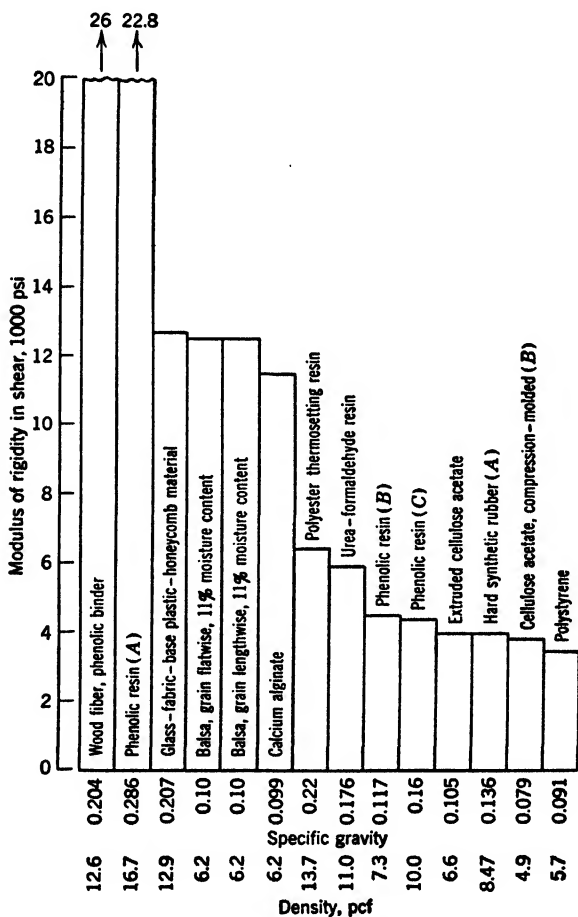


FIG. 20-4. Modulus of Rigidity in Shear of Low-Density Core Materials. (Modulus associated with shear distortion of planes parallel to edge of material.)

plastic tubing together lengthwise into a bundle or block of tubes from the edge of which pieces of core material are sawed. Another consists of thin plywood panels glued in alternate layers to strips of spruce, balsa, or low-density cellular plastic to make up a strip-panel assembly. When pieces are sawed from an edge of this assembly, a grid-type core

material is obtained. Latticework, grids, and other forms have been made from thin sheet metal and from vulcanized fiber as well as from wood strips, plywood, and laminated plastics. It should also be noted

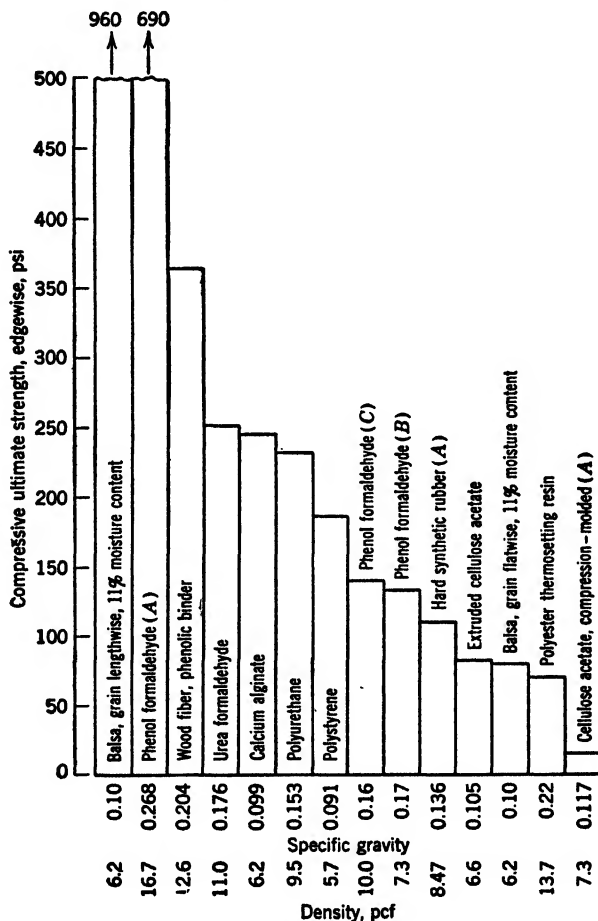


FIG. 20-5. Compressive Ultimate Strength of Low-Density Core Materials. Tested in edgewise direction.

that the open spaces in these grids may be filled with low-density cellular plastic for further support of the faces of the sandwich construction in which they are to be used. Another combination of interest is that termed wrapped construction. As a specific example, application has been made of strips of cellular cellulose acetate  $\frac{3}{4}$  in. wide, and of length and thickness as desired, spirally wrapped with one layer of a

thin (0.003 in.) glass fabric impregnated with a polyester resin (not cured). These wrapped strips are laid up between uncured polyester-resin-impregnated glass-fabric laminated faces, and the whole sand-

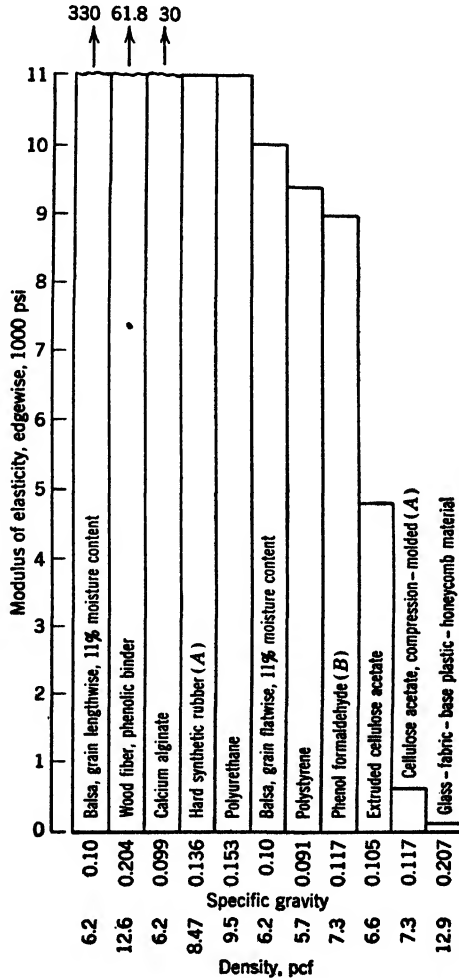


FIG. 20-6. Modulus of Elasticity of Low-Density Core Materials. Tested in edgewise direction.

wich construction is cured and bonded together simultaneously by bag molding.<sup>92, 98</sup> This procedure results in a sandwich in which the faces are interwoven integrally with the core, and the faces are then securely attached to the core.



## PROPERTIES OF CORE MATERIALS

In order for the low-density core material to stabilize the sandwich-construction faces so that the latter will be enabled to develop their

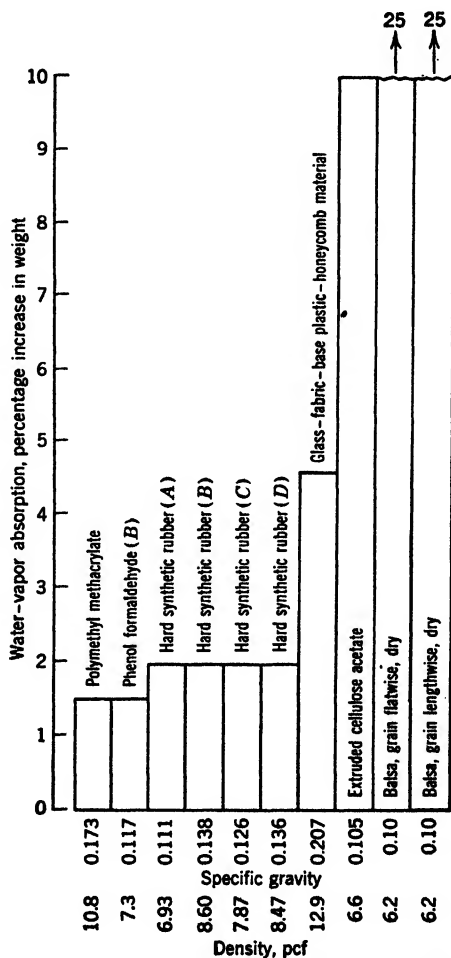


FIG. 20-7. Water-Vapor Absorption of Low-Density Core Materials. 24 hr at 160°F and approximately 100 per cent relative humidity.

yield or ultimate strength before the sandwich panel buckles, or before the faces wrinkle or separate from the core, a high tensile strength of the core in the direction perpendicular to the faces is required, and also a high modulus of rigidity in shear associated with shear distortion of

planes parallel to the edge of the core material in the sandwich construction. A high shear modulus is important also in maintaining a high stiffness factor ( $EI$ ) of the sandwich construction in bending or flexure, because shear is always involved in bending except for the special case of pure bending. Another consideration is that the core

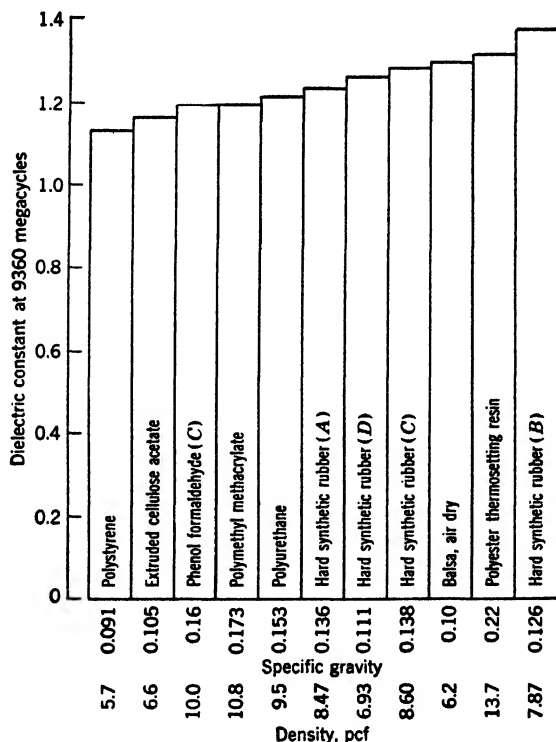


Fig. 20-8. Dielectric Constant of Low-Density Core Materials.

material must not be so brittle that it fails in compression edgewise before the face material, whether the latter is metal, plastic, or wood, develops its yield or ultimate strength. This means that the strain at failure in compression edgewise must be of the order of at least about 1 to 2 per cent. Note that the compressive strength edgewise and modulus of elasticity edgewise are not particularly important, unless for greatest efficiency it is required that the core material itself carry an appreciable part of the load. This only occurs for sandwich combinations involving very thin faces and strong cores, as balsa with grain parallel to load. Sufficient compressive strength and stiffness

flatwise are also required for support of the faces and for resistance to handling loads. Also, brittle and crumbly materials fail in the core material and in the bond to the faces on relatively light impact loads flatwise, so that toughness is a desirable characteristic. High shear

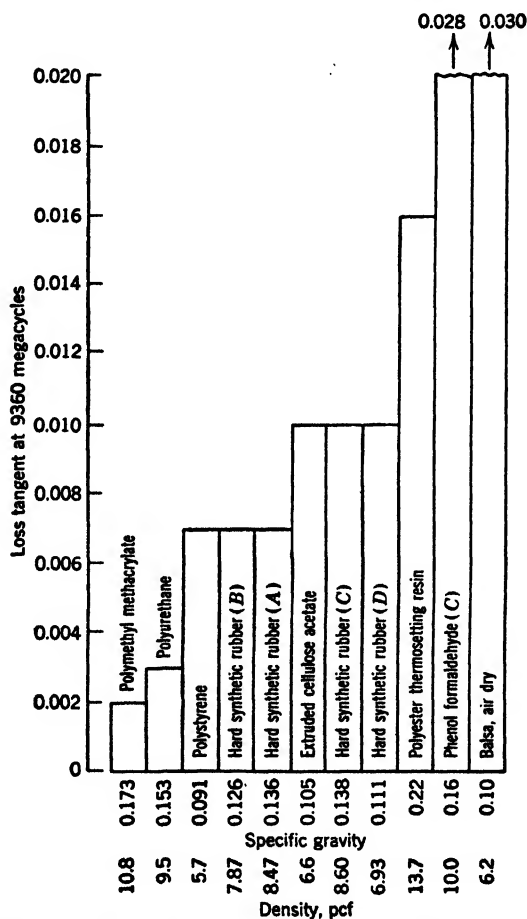


FIG. 20-9. Loss Tangent of Low-Density Core Materials.

strength of the core material is necessary to provide support for lateral forces and to transfer stresses from one face to the other. This is particularly important in bending. Satisfactory sawing, forming, bonding, and other fabricating qualities are necessary, and the core material must produce sandwich construction resistant to weathering, including varied temperature and humidity. Very important, of course, is that

the density be as low as possible, in order to save weight, and that the cost be reasonable.

Some of the significant properties of some typical low-density core materials are presented in Tables 20-2 to 20-7 and Figs. 20-1 through 20-9, inclusive. In determining the properties of low-density core materials special precautions must be observed, and special test procedures have been developed for them.<sup>27, 82</sup> The testing is complicated by the fact that the critical properties are in certain directions, and, unless the material is isotropic, the tests must be made so that loads are applied in the desired directions, in order that the material may be properly evaluated or correct design data obtained. Some of the core materials are obviously anisotropic, as balsa and honeycomb, but others, such as extruded cellular cellulose acetate, cellular hard synthetic rubber, and so on, also exhibit anisotropy to a certain degree.

**TABLE 20-2. COMPRESSIVE HEAT-DISTORTION TEMPERATURE AT 0.1% COMPRESSION FOR LOW-DENSITY CORE MATERIALS**

15 psi compressive stress, temperature raised 2°F per minute. All specimens loaded flatwise (in thickness direction)

Material	Average Temperature, °F
Glass-fabric-base plastic-honeycomb material	280
Polyurethane resin	190
Hard synthetic rubber	180
Compression-molded cellulose acetate, white, 4.6 pcf	180
Polystyrene	175
Polymethyl methacrylate	155
Phenolic resin	150
Extruded cellulose acetate	130
Compression-molded cellulose acetate, gray, 7.3 pcf	130
Polyvinyl formal	130
Urea-formaldehyde resin	125
Calcium alginate	110
Wood fiber, phenolic resin binder	105

The glass-fabric-base plastic-honeycomb-core material listed in the figures and tables was fabricated from polyester-resin-impregnated glass fabric, 0.003 in. thick, and made into laminated glass-fabric-base polyester-plastic-faced sandwich construction. The latter was tested so that the properties of the core material were obtained. As in the usual practical applications of honeycomb core with plastic faces, it was not possible to develop the full tensile strength flatwise of the honeycomb material because of failure in the bond to the faces. This

TABLE 20-3. THERMAL CONDUCTIVITY OF LOW-DENSITY MATERIALS

Principally from References 11, 47 and 75

Material	Specific Gravity	Thermal Conductivity, Btu per sq ft per hr for 1 in. Thickness and 1°F Temp. Difference	Mean °F
Cellular cement or concrete	0.25	0.47	75
Cellular glass	0.17	0.49	32
	0.20	0.52	32
Soft cellular rubber	0.11	0.27	50
Cellular hard natural rubber	0.06	0.19	50
	0.07	0.21	23
Cellular hard synthetic rubber	0.07	0.23	50
	0.09	0.22	52
Calcium alginate			
17% water content	0.10	0.28	72
26% water content	0.11	0.29	72
Polyvinyl formal	0.06	0.26	50
	0.10	0.24	50
	0.14	0.24	50
	0.20	0.34	50
Phenolic resin	0.08	0.24	46
	0.08	0.28	115
	0.11	0.27	86
	0.11	0.29	115
	0.19	0.30	50
Polystyrene	0.05	0.30	50
	0.08	0.29	32
	0.10	0.31	50
Chlorinated rubber	0.11	0.27	50
	0.18	0.28	50
Compression-molded cellulose acetate	0.085	0.40	..
Polystyrene	0.016	0.35	..
Cellular hard synthetic rubber	0.069	0.25	..
Balsa	0.093	0.32	..
Balsa	0.16	0.41	..
Extruded cellulose acetate	0.07	0.30	
	0.10	0.31	
	0.12	0.32	
		Coefficient of Thermal Expansion per °F	
Compression-molded cellulose acetate	0.10	$7.2 \times 10^{-5}$	
Extruded cellulose acetate	0.10	$2.5 \times 10^{-5}$	
	0.12	$2.5 \times 10^{-5}$	

TABLE 20-4. EFFECT OF HONEYCOMB CELL SIZE

Glass-Fabric-Base Plastic Honeycomb

Nominal cell size, in.	$\frac{3}{16}$	$\frac{1}{4}$
Fabric thickness, in.	0.003	0.003
Resin content of fabric, %	78	76
Apparent density, pcf	12.9	8.4
Specific gravity	0.206	0.134
Tensile strength, flatwise, psi	379 *	271 *
Compressive strength, flatwise, psi	1248	564

\* Failed in bond between honeycomb core and plastic faces.

TABLE 20-5. SHEAR STRENGTHS OF LOW-DENSITY MATERIALS OF 0.10 SPECIFIC GRAVITY

<i>Balsa</i>	
Parallel to grain, tangentially, psi	210
Parallel to grain, radially, psi	175
<i>Paper-Base Plastic Honeycomb</i>	
In direction of cells and corrugated sheets, psi	270
In direction of cells and perpendicular to corrugated sheets, psi	200
<i>Extruded Cellulose Acetate</i>	
Longitudinal direction, psi	125
<i>Hard Synthetic Rubber</i>	
Longitudinal direction, psi	125
<i>Glass-Fabric-Core Plastic Honeycomb</i>	
In direction of cells and corrugated sheets, psi	85
In direction of cells and perpendicular to corrugated sheets, psi	195

TABLE 20-6. SPECIFIC STRENGTH VERSUS SPECIFIC GRAVITY OF SOME LOW-DENSITY MATERIALS

1	2	3	4	5
Specific Gravity	Tensile Strength, psi	Compressive Strength, psi	Specific Tensile Strength, psi (2/1)	Specific Compressive Strength, psi (3/1)
<i>Extruded Cellular Cellulose Acetate</i>				
0.064	60	80	940	1250
0.096	110	150	1150	1560
0.128	250	270	1950	2110
<i>Polyurethane</i>				
0.06	40	...	67.0	....
0.10	115	...	1150	....
0.15	200	...	1330	....
0.18	255	...	1420	....

is due to the limited bonding area of the honeycomb core. Comparative properties of  $\frac{3}{16}$ - and  $\frac{1}{4}$ -in. nominal cell sizes of glass-fabric-base plastic honeycomb are given in Table 20-4. These materials are shown in Fig. 20-10 at a magnification of  $3\times$ . The properties of the heavier material are given in Fig. 20-1 through 20-9. Equivalent or better properties may also be possible of attainment with paper- or cotton-fabric-base plastic honeycomb. The latter core material with approximately  $\frac{1}{2}$ -in. cell size is finding increasing applications.

TABLE 20-7. EFFECTS OF MOISTURE AND HEAT ON LOW-DENSITY MATERIALS OF 0.10 SPECIFIC GRAVITY

Conditioning *	Compressive Strength, Flatwise, psi	Shear Rigidity, psi	Tensile Strength, Flatwise, psi
<i>Balsa, Grain Flatwise</i>			
A	935	19,300	1,450
B	469	12,500	1,670
C	629	13,700	1,040
D	890	17,800	860
E	1,148	14,200	980
<i>Hard Synthetic Rubber</i>			
A	199	3,380	331
B	157	3,390	187
C	155	2,910	210
D	188	3,720	288
E	68	1,250	102
<i>Extruded Cellulose Acetate</i>			
A	164	4,390	316
B	88	2,880	184
C	114	2,800	218
D	167	4,040	274
E	160	4,250	266

\* A = equilibrium with 75°F and 65% relative humidity

B = 24 hr immersion in water, tested wet

C = equilibrium with 80°F and 97% relative humidity, tested immediately

D = equilibrium with 80°F and 97% relative humidity, tested after reconditioning to equilibrium at 75°F and 65% relative humidity

E = 240 hr at 200°F, tested at 200°F

The calcium alginate foam was made by whipping a solution of ammonium alginate to a foam and adding a calcium salt which causes the foam to harden to calcium alginate. The cells are very fine relative to those of the other materials and are not interconnected. The ma-

terial has high water and water-vapor absorption and becomes soft when wet.

The cellular polyvinyl formal was made by foaming a partially hydrolyzed polyvinyl acetate and setting by the addition of strong acid to produce polyvinyl formal. The cells in this material are interconnected.

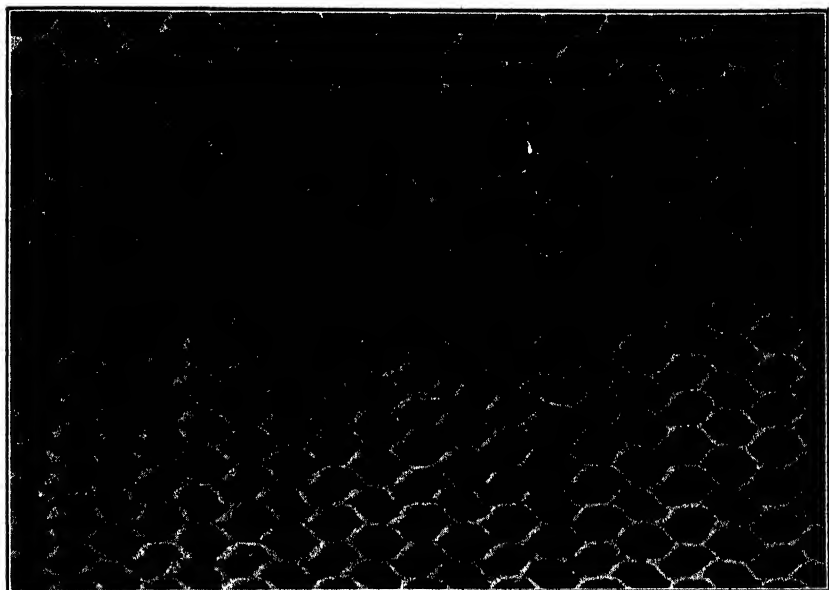


FIG. 20-10. Glass-Fabric-Base Plastic Honeycomb,  $\frac{3}{16}$ - and  $\frac{1}{4}$ -in. Nominal Cell Size. Magnification  $1\frac{1}{2}\times$ .

Figures 20-11, 20-12, and 20-13 show the differences in the structures of expanded phenolic resins A, B, and C, respectively. All these photographs are at a magnification of  $20\times$ , as are the remainder of the photographs of low-density core materials given, and so these may all be directly compared as to cell size and structure of the various materials. The natural unexpanded surfaces or skins of all the materials were removed before the photographs were taken.

The structure of the foamed cast-polyester-resin alkyd-styrene type is shown in Fig. 20-14 and that of the foamed cast-urea-formaldehyde resin in Fig. 20-15. Figures 20-16, 20-17, and 20-18 show the reason for the directional properties of the extruded cellular cellulose acetate. This material was extruded into long lengths about  $2\frac{1}{2}$  in. wide by  $\frac{1}{2}$  in. thick. Figure 20-16 shows a view of a section of the edge of this



material ( $\frac{1}{2}$ -in. by extruded length dimension). Figure 20-17 shows a section of the  $2\frac{1}{2}$ -in. by extruded length surface, and Fig. 20-18 shows an end-on view of a section of the  $\frac{1}{2}$ -in.-by  $2\frac{1}{2}$ -in. surface. It may be seen that the cells are elongated in the extruded direction. The density gradient in the extruded direction is less than in the other two directions. As may be expected, the material is stronger and stiffer in

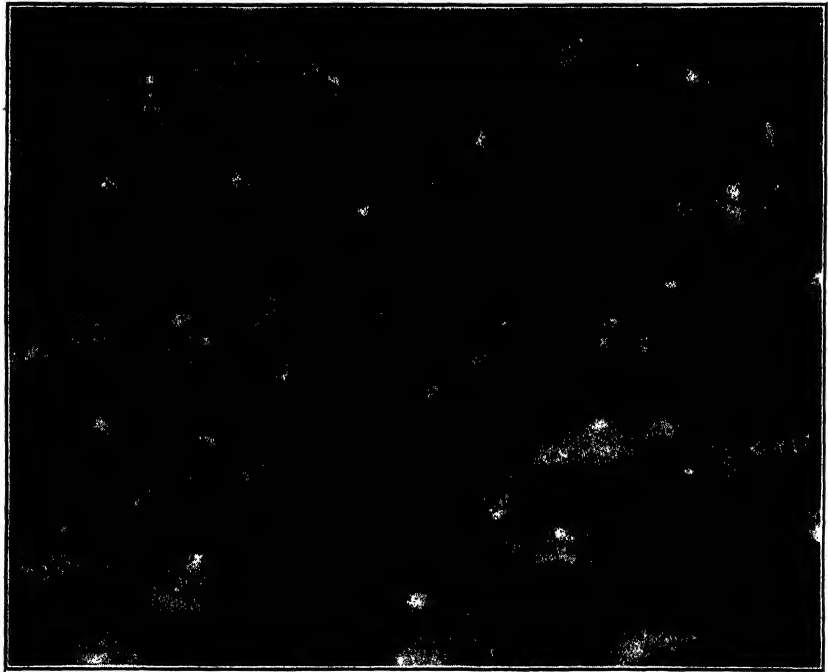


FIG. 20-11. Expanded Phenolic Resin A. Magnification  $20\times$ .

the width and thickness directions than in the lengthwise direction, but the properties in the width and thickness directions are comparable.

The edge and surface views of the low-density wood fiberboard, phenolic-resin-impregnated, are shown in Figs. 20-19 and 20-20, respectively. The thickness direction of the edge view is the direction of the long dimension of the photographs. It may be seen that the low tensile strength in this direction is explainable by the fact that the fibers for the most part do not run in the thickness direction and also there are more voids per inch in the thickness direction.

The surface and edge views of the cellular hard synthetic rubber B are shown in Figs. 20-21 and 20-22, respectively. This material was

butadiene-acrylonitrile base, compression-molded by the two-stage process. It may be seen that the edge view of the cells, as shown in Fig. 20-22, are somewhat flattened, compared with the surface view in Fig. 20-21. It would be expected, therefore, that the mechanical properties would be somewhat higher flatwise. The average cell size of this material is less than that of the hard synthetic rubber C, shown

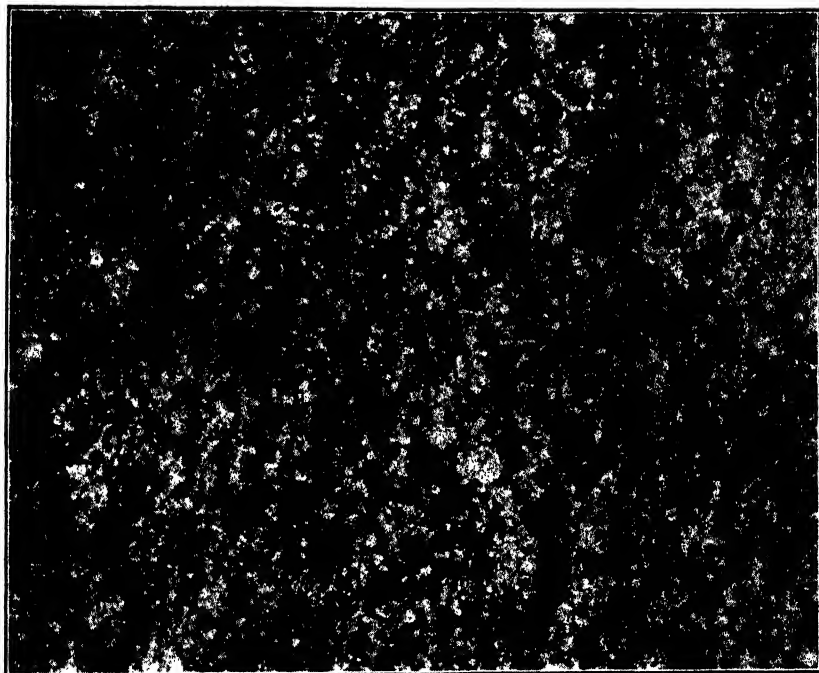


FIG. 20-12. Expanded Phenolic Resin B. Magnification 20 $\times$ .

in surface and edge views in Figs. 20-23 and 20-24, respectively. Hard synthetic rubber A corresponds in cell size approximately to material B, and the cell size of material D corresponds approximately to that of material C. All these are butadiene-acrylonitrile-base thermosetting hard-synthetic-rubber materials, which were chemically blown during cure under heat and pressure. The cells are noninterconnecting, in general. It should be noted that similar hard-synthetic-rubber materials can be and have been made with properties and structure different from those described, especially with regard to strength, heat resistance, hardness, cell size, and cell structure.

No photographs are shown of the structures of the other low-density materials. However, the foamed and cast low-density polyurethane had relatively large and nonuniform cells, whereas those of the polyvinyl formal and methyl methacrylate were relatively small and uniform. The calcium alginate had an uniform and very small cell size. That of the polystyrene was somewhat larger than that of the other

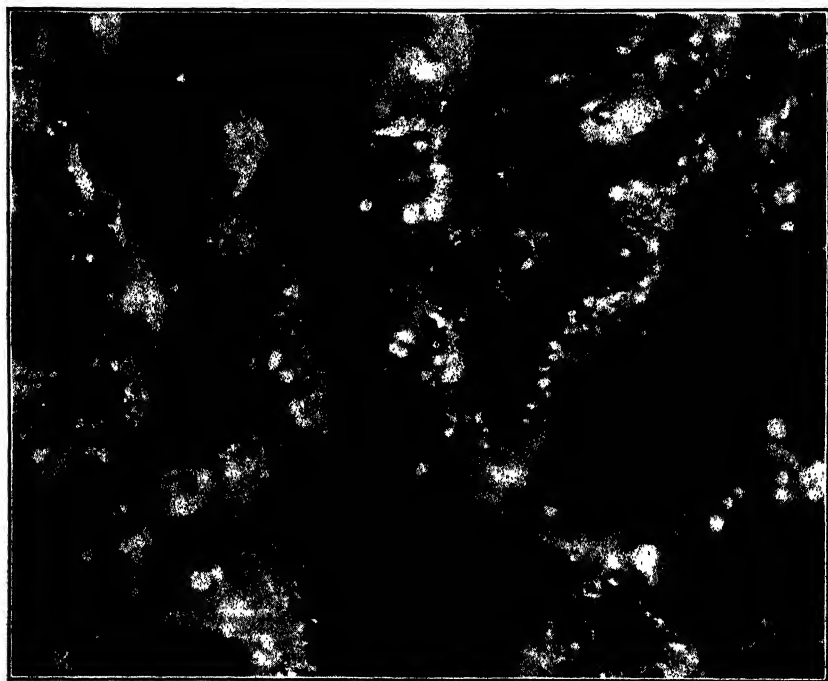


FIG. 20-13. Expanded Phenolic Resin C. Magnification 20 $\times$ .

thermoplastics. The two compression-molded cellulose acetate materials were very similar and extremely anisotropic, showing a grain effect comparable to balsa wood. These compression-molded cellulose acetate materials exhibited a definite grain or fiber effect in the thickness direction and were many times stronger in this direction than in the other two directions. These cellulose acetate materials did not contain any glass-fiber filler.

The compressive heat-distortion curves shown in Fig. 20-1 are of value in comparing the heat resistance of the various materials. The curves for hard synthetic rubbers A, B, C, and D are all approximated by the one curve for hard synthetic rubber shown. However, other

formulations may be made of higher or lower heat resistance, as desired, usually with some adverse effects on some of the other properties. The heat-distortion curves for extruded cellulose acetate, 6.2 pcf density, and for compression-molded cellulose acetate, 7.3 pcf density, were practically identical, and, therefore, only one curve is shown for both. No explanation is offered for the fact that the curve for compression-

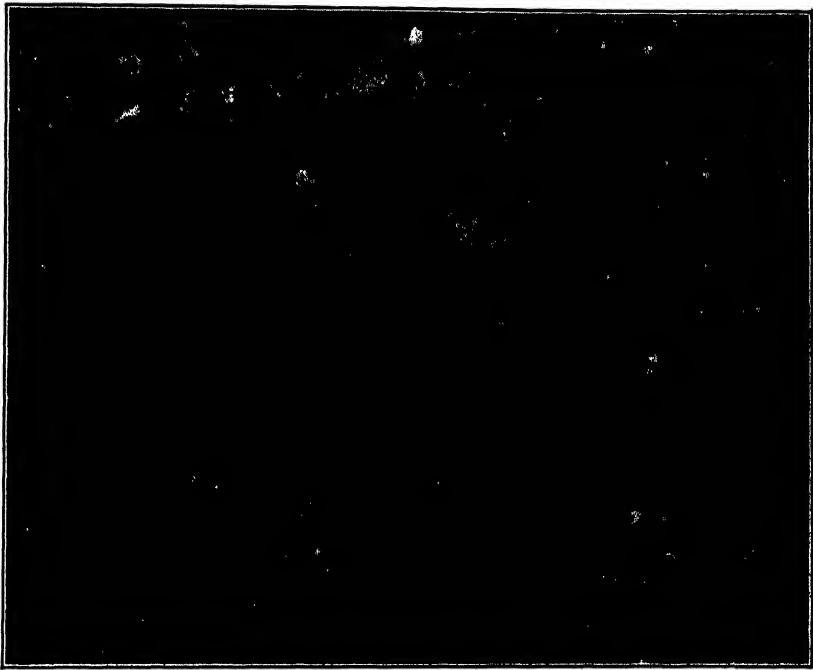


FIG. 20-14. Foamed Cast Polyester Resin, Alkyd-Styrene Type. Magnification 20X.

molded cellulose acetate of 4.91 pcf density lies above the curves for the 7.3-lb material, except that the two base materials were not identical. The heavier material was white in color, and the lighter material was gray.

The honeycomb core exhibited only negative compression (that is, expansion), because the increase in thickness due to thermal expansion was greater than the compression due to the load. This condition also occurred up to a certain point only for some of the other core materials. Negative compressions are shown by dotted curves.

It may be noted that the best heat resistance, next to the honeycomb, was exhibited by the cellular cellulose acetate materials. These are

thermoplastic materials, but they contain no plasticizer and require heating up to approximately 350° to 400°F for forming. It is also important to note that materials such as the polystyrene, polymethyl methacrylate, and polyvinyl formal tested would generally be unsuited for bag molding or other molding of sandwich construction under even low pressure at elevated temperatures. The polymethyl methacrylate



FIG. 20-15. Foamed Cast Urea-Formaldehyde Resin. Magnification 20X.

also develops considerable shrinkage in dimensions at temperatures as low as 160°F under no stress, after a period of time at temperature.

Since it is difficult to distinguish between the first parts of the heat-distortion curves in Fig. 20-1, Table 20-2 lists the temperatures for 0.1 per cent compression, at 15 psi compression stress.

Although curves for balsa are not available, it is considered that for either grain direction they would lie close to the temperature axis, so that balsa is believed to be at least as heat-resistant as the cellulose acetate materials. This is also indicated by experience in molding sandwich construction with balsa core under heat and pressure.

The charts showing some of the mechanical properties of some of the core materials, as given in Figs. 20-2 to 20-6, inclusive, are self-explanatory. The significance of these properties has been discussed. Water-vapor absorption, shown in Fig. 20-7, is considered more important than water absorption by immersion, since the materials are used between two faces in sandwich construction. The dielectric-con-

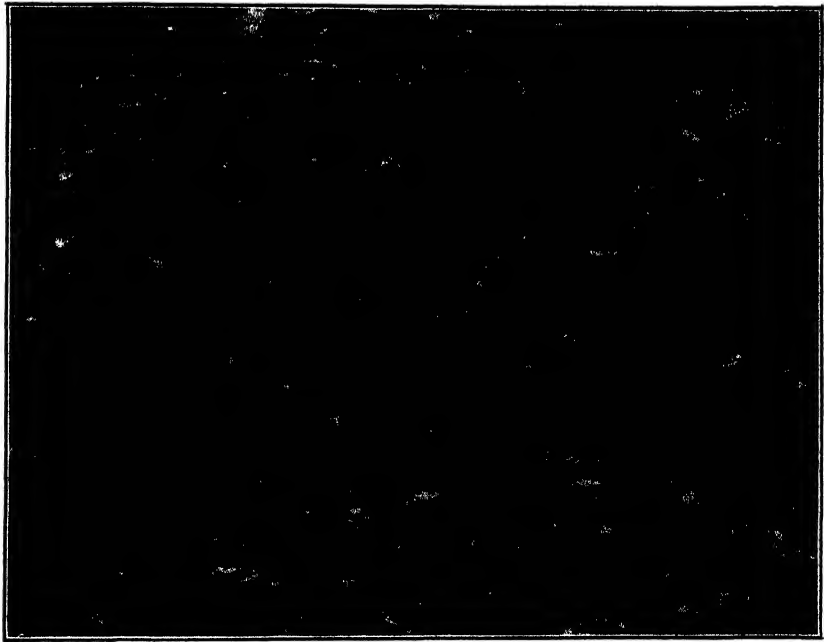


FIG. 20-16. Extruded Cellulose Acetate, Edge View, Extruded Length Direction in Direction of Long Dimension of Photograph. Magnification 20X.

stant and loss-tangent properties at a very high frequency (9360 megacycles) are shown in Fig. 20-8 and 20-9, and their significance is discussed under radar-antenna housings.

Shear-strength data available on a few materials are given in Table 20-5. Heat-conductivity and thermal-expansion coefficients are given in Table 20-3. As would be expected, the low-density core materials are good heat insulators. Although no quantitative impact data are given here, sandwich constructions made with honeycomb, balsa, and thermoplastic core materials such as cellulose acetate are considered to be more impact-resistant than those made with thermosetting core materials as phenolic urea or polyester resins. Cellular hard-synthetic-

rubber materials of the types whose properties have been given are thermosetting but are tougher than most of the thermosetting-resin low-density materials, but not so tough as the first group of materials mentioned. Some impact data are reported in reference 56. Although few data are available as yet, it is to be expected that the strength of



FIG. 20-17. Extruded Cellulose Acetate, Top View, Extruded Length Direction in Direction of Long Dimension of Photograph. Magnification 20 $\times$ .

low-density core materials will decrease with increasing number of cycles of alternating loading (fatigue) and with duration of time of constant loading (creep). The creep deformations occurring with time under these conditions may need to be considered in some applications. Some fatigue data are reported in references 73, 81, and 88 and some creep data in reference 88.

Also important are the effects of water, high humidity, weathering, and temperature on the properties of low-density core materials. Some data on these effects are reported in references 29, 32, 57, 58, 63, 64, 71, 73, 74, 77, 78, 80, 88, and 90.

It has been shown for many different low-density synthetic resins that the strength properties decrease much more rapidly with decreas-

ing density than a linear relationship which might perhaps be expected. In other words the strength-density ratios decrease with decreasing density. Table 20-6 shows an example (data taken from reference 64). Properties of various low-density core materials versus density are also given in references 21, 31, 37, 41, 53, 64, 74, 76, 77, and 78.

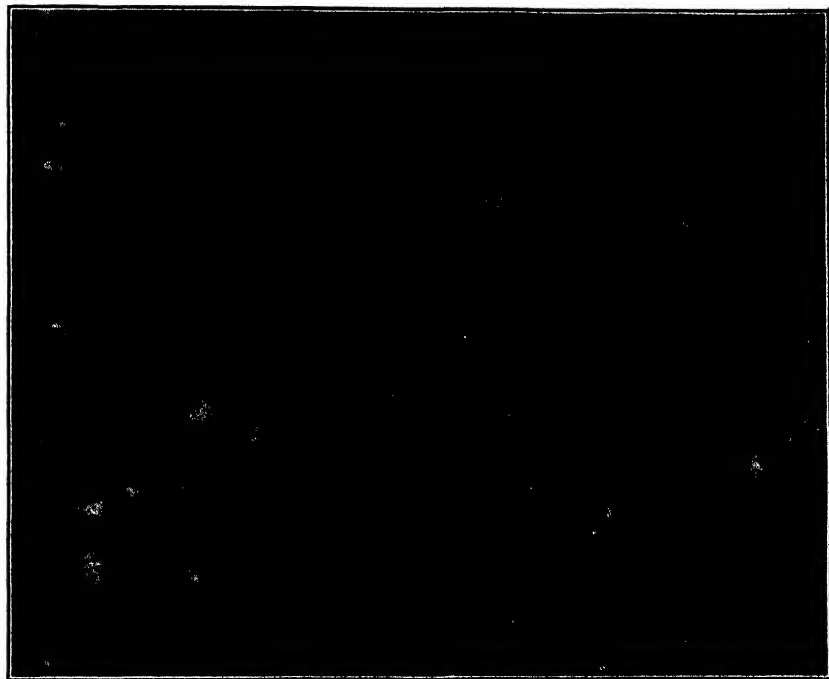


FIG. 20-18. Extruded Cellulose Acetate, End View. Magnification 20X.

In general also, a nonconnecting cell structure results in better mechanical properties than a connecting cell structure. Some cellular materials can be made both ways, as, for example, synthetic rubber.

Some cellular synthetic materials may be produced in two forms with different average cell sizes but the same weight per cubic foot. Obviously, the cell walls of the material of the finer structures are thinner. For such materials of comparable composition and density, the one with the finer structure or smaller average cell size is generally stronger. Some indication of this is shown in the properties of the cellular hard-synthetic-rubber materials which have been given herein and also those data given in reference 31.

From the point of view of mechanical properties alone, it is considered that balsa is the best low-density structural-sandwich core ma-



terial. Its disadvantages are its variability in density, defects, and properties and its high water-vapor absorption. It must be imported, and the process of selection to obtain the desired density and quality requires that most of the balsa as received be rejected. Of the synthetic materials, paper- or cotton- or glass-fabric-base plastic honeycomb, extruded cellular cellulose acetate, compression-molded cellulose

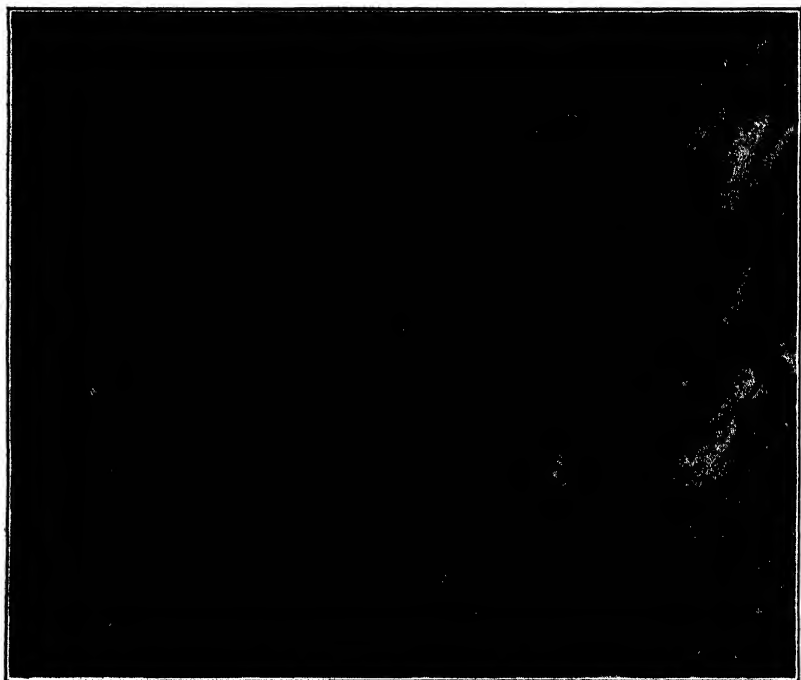


FIG. 20-19. Low-Density Wood Fiberboard, Edge View. Magnification 20 $\times$ .

acetate and cellular hard synthetic rubber exhibit the best balance of mechanical and physical properties, although each has certain advantages and disadvantages compared to the others.

It is also significant that balsa, honeycomb (of several types), extruded cellulose acetate, and cellular hard synthetic rubber are the only core materials, of those for which properties are given in Figs. 20-1 to 20-9, in production for structural use in the United States.

Table 20-8 lists the number of those references given in the list of references and bibliography which are applicable to properties of core materials.

No detailed properties are available yet on recently developed honeycomb core materials made from aluminum-alloy thin sheet, 0.005 or 0.006 in. thick. The sheets are corrugated, the corrugations glued together into blocks with a hot-setting metal-to-metal adhesive, and honeycomb sections are sawed from the end of the block as is done for other honeycomb cores. Such alloys as 2S, full hard, and 52S,  $\frac{3}{4}$  hard, have been used. High flatwise compressive strength and edgewise modulus of rigidity are obtained as compared with other honeycomb cores. Core densities can be obtained within the same range as for other honeycomb cores.

TABLE 20-8. CLASSIFICATION OF REFERENCES AND BIBLIOGRAPHY

Subject	Reference Numbers
Properties of core materials	1, 11, 13, 14, 19, 21, 24, 25, 27, 28, 31, 35, 36, 37, 38, 41, 42, 44, 45, 47, 51, 53, 54, 55, 56, 58, 63, 64, 65, 67, 69, 70, 71, 73, 74, 75, 76, 77, 78, 80, 81, 82, 88, 90, 94, 96, 100.
Design criteria and test data on sandwich constructions	3, 4, 5, 6, 9, 12, 15, 16, 17, 18, 20, 23, 26, 29, 30, 31, 33, 34, 38, 39, 40, 42, 44, 45, 46, 48, 49, 50, 55, 56, 57, 58, 66, 71, 73, 74, 76, 78, 79, 80, 83, 84, 85, 86, 87, 88, 89, 90, 91, 93, 95, 96, 97, 100.
Sandwich-construction applications	2, 7, 8, 10, 22, 32, 52, 55, 57, 60, 61, 62, 68, 72, 86, 87, 92, 95, 98, 99, 101, 102.
Sandwich-construction fabrication	10, 22, 32, 43, 44, 50, 52, 55, 57, 59, 65, 70, 87, 92, 98, 99, 101, 102.

#### SANDWICH-CONSTRUCTION APPLICATIONS

Successful use of structural-sandwich construction was made by the British deHavilland Aircraft Company in the Albatross airplane before 1940. Plywood-faced balsa core sandwich construction was employed, as was also in the later very successful Mosquito deHavilland aircraft. Increasing attention has since been given to the use and advantages of sandwich construction of all types in aircraft structures and parts. Of course, other applications have been and are being exploited, but none are considered so critical in all requirements as the aircraft applications.

Compared to such types of structural construction as fabricated trusswork, welded-tubular, geodetic, and thin sheet with stringer reinforcements, sandwich-construction structures show certain advantages. The greatest of these are the fundamental fabrication and design advantages resulting from the fact that relatively large integral structural parts can be molded or fabricated in one or, at most, a very few operations, with a minimum of component parts, stiffeners, ribs,

terial. Its disadvantages are its variability in density, defects, and properties and its high water-vapor absorption. It must be imported, and the process of selection to obtain the desired density and quality requires that most of the balsa as received be rejected. Of the synthetic materials, paper- or cotton- or glass-fabric-base plastic honeycomb, extruded cellular cellulose acetate, compression-molded cellulose

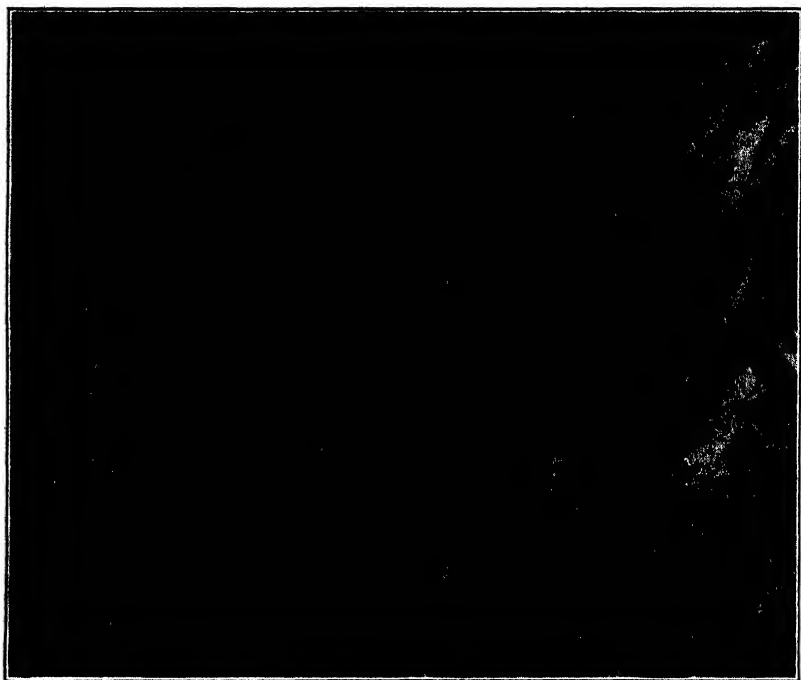


Fig. 20-19. Low-Density Wood Fiberboard, Edge View. Magnification 20 $\times$ .

acetate and cellular hard synthetic rubber exhibit the best balance of mechanical and physical properties, although each has certain advantages and disadvantages compared to the others.

It is also significant that balsa, honeycomb (of several types), extruded cellulose acetate, and cellular hard synthetic rubber are the only core materials, of those for which properties are given in Figs. 20-1 to 20-9, in production for structural use in the United States.

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Design criteria and test data on sandwich constructions	3, 4, 5, 6, 9, 12, 15, 16, 17, 18, 20, 23, 26, 29, 30, 31, 33, 34, 38, 39, 40, 42, 44, 45, 46, 48, 49, 50, 55, 56, 57, 58, 66, 71, 73, 74, 76, 78, 79, 80, 83, 84, 85, 86, 87, 88, 89, 90, 91, 93, 95, 96, 97, 100.
Sandwich-construction applications	2, 7, 8, 10, 22, 32, 52, 55, 57, 60, 61, 62, 68, 72, 86, 87, 92, 95, 98, 99, 101, 102.
Sandwich-construction fabrication	10, 22, 32, 43, 44, 50, 52, 55, 57, 59, 65, 70, 87, 92, 98, 99, 101, 102.

### SANDWICH-CONSTRUCTION APPLICATIONS

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Compared to such types of structural construction as fabricated trusswork, welded-tubular, geodetic, and thin sheet with stringer reinforcements, sandwich-construction structures show certain advantages. The greatest of these are the fundamental fabrication and design advantages resulting from the fact that relatively large integral structural parts can be molded or fabricated in one or, at most, a very few operations, with a minimum of component parts, stiffeners, ribs,

rivets, and so on. The stiffness and strength characteristics of structural-sandwich construction allows the elimination of great numbers of such stiffening and strengthening members, and also of rivets, welds, and fastenings. Thus, half a fuselage or a wing may be made in one piece, for example. These factors tend to reduce design detail and fabrication costs. Other fundamental advantages are aerodynamic ad-



FIG. 20-20. Low-Density Wood Fiberboard, Surface View. Magnification 20 $\times$ .

vantages due to the smoothness, resulting from the elimination of the buckling or oil canning of the thin sheet of sheet-stringer construction under load. The sandwich-construction structure can also usually be made smoother, as manufactured in the unloaded condition owing to elimination of rivets and laps and molding in one piece. Finally, for many specific applications, the sandwich construction is lighter for the same strength or stronger for the same weight, because of the high stiffness or  $EI$  factor resulting from separation of the faces by the core; also, in general, the faces or the panel do not buckle before the yield or ultimate strength of the face material is reached; in addition, greater increase in strength due to curvature is realized than in the case

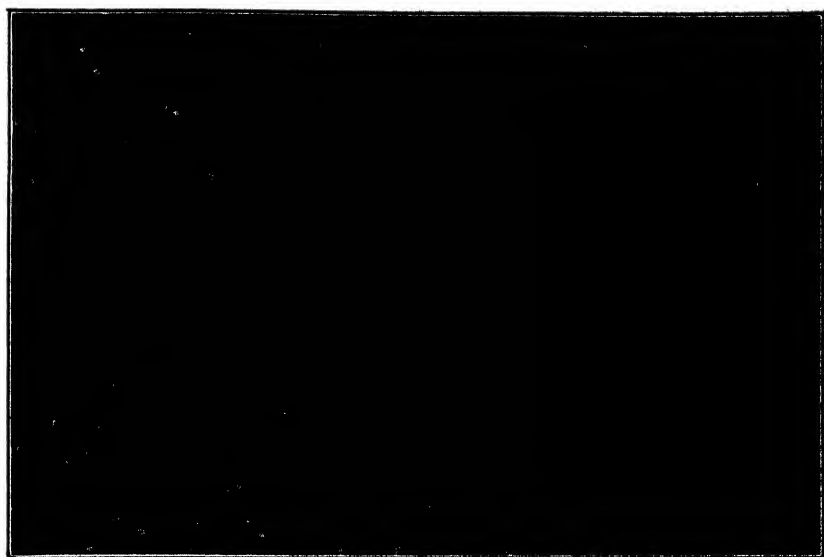


FIG. 20-21. Cellular Hard Synthetic Rubber B, Surface View. Magnification 20X.

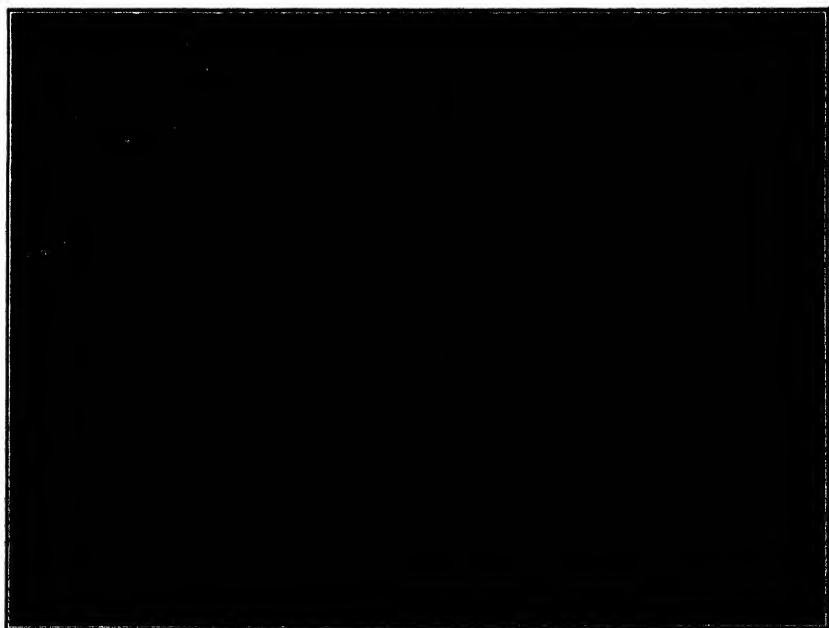


FIG. 20-22. Cellular Hard Synthetic Rubber B, Edge View. Magnification 20X.

of sheet-stringer construction for curved panels compared to flat of the same construction.

There are also disadvantages. A temporary one has been the lack of sufficient fundamental theoretical design criteria checked by experimental tests. Designs have been largely based on empirical data and tests of components, and this has been an unsatisfactory footing on which to base widespread application of sandwich construction in air-



Fig. 20-23. Cellular Hard Synthetic Rubber C, Surface View. Magnification 20 $\times$ .

craft. The number of variables, as face and core materials and thicknesses, is so great, that it is impossible to present sufficient empirical data to cover all cases, even all the useful ones. However, this situation is being rapidly rectified through work by the Forest Products Laboratory for the Army-Navy Civil Committee on Design Criteria and by some of the aircraft companies themselves.

Another disadvantage has been the relative difficulty of design of assembly fittings for sandwich construction and for the effective transfer of loads into the sandwich from other parts. This difficulty will probably be minimized with experience, however. Similarly, difficulties with fabrication techniques such as bonding have been principally due to inexperience. However, a fundamental disadvantage to which there does not appear to be a good answer at present is the inspection problem. The stiffness and strength advantages of sandwich construction are not gained unless a good adhesive bond is secured between the faces and the

core material. Usually it is desired that the bond be as strong as the core material. The core and face materials may perhaps be inspected separately (although not in all cases) as may be the quality of the adhesive to be used, but the face-to-core bond of the finished sandwich construction may only be effectively inspected by cutting out test specimens for destructive tests or strength-testing the assembly. In

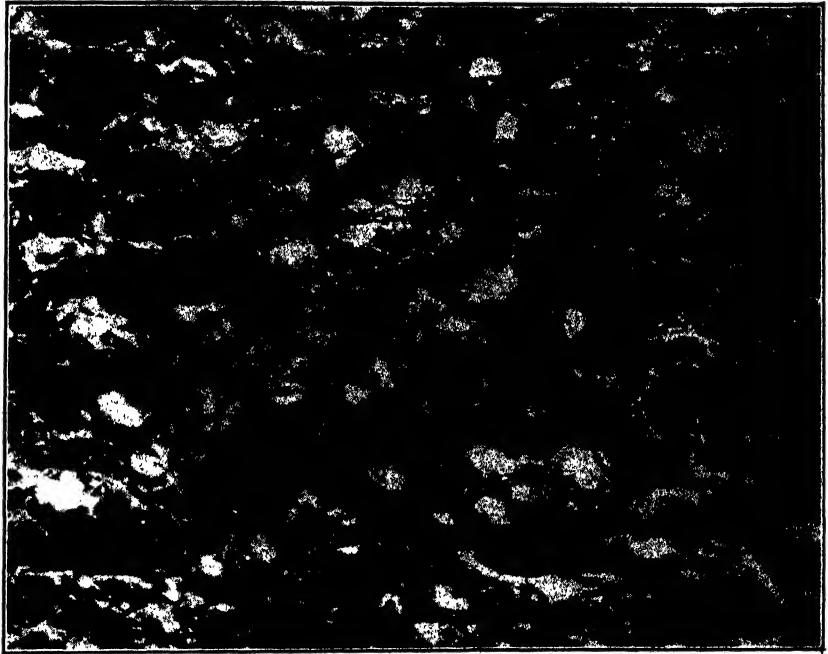


FIG. 20-24. Cellular Hard Synthetic Rubber C, Edge View. Magnification 20X.

the case of plastic-faced sandwich construction produced by a wet lay-up procedure, the quality of the face material itself is subject to a similar inspection limitation. Even where small test specimens may be provided from trim areas or samples are made simultaneously with the sandwich-construction part, there is still a question as to whether all critical areas of the part itself are well bonded. Since such destructive testing that may be made are either impractical or inadequate in actual production, attempts have been made to find some suitable non-destructive means of inspection. Such methods as tapping, supersonic testing, suction cup, and sudden pressure release in autoclaves have been investigated. However, in general, it has been possible to locate only areas of no bond or of very poor bond. This, of course, is of



value, but, if the part passes one of these types of inspection, there is still the question of whether the bond is as good as it should be or even up to the minimum necessary for carrying the design loads. In view of this situation, it must be emphasized that it is absolutely necessary to control carefully the materials and the processes employed. After consistency and quality of both have been thoroughly checked experimentally by tests of specimens and the actual parts to be made, the materials and processes found satisfactory experimentally must be rigidly controlled thereafter in production. Of course, this does not eliminate any such testing and inspecting that may be practically made in addition. This condition is paralleled at least to some extent in the case of production of structural castings, welded parts, and conventional glued-wood construction.

The greater the number of successful service applications that are made of sandwich construction, the more confidence will there be generated in it and in the fabrication procedures and the materials and processes controls which are required, and this will result in still further applications. Some of the more important applications which have been made will be cited. The deHavilland Aircraft utilizing plywood-balsa sandwiches have been mentioned, the Mosquito aircraft being especially famous. More recently Chance-Vought Aircraft Division of United Aircraft Corporation have utilized aluminum-alloy-balsa (grain perpendicular to faces) sandwich construction for practically all the structure of the XF5U-1 Navy fighter and of the high performance XF6U-1 Navy jet fighter. In addition, regular production was established on Corsair horizontal tail surfaces, and these were in Navy service by the hundreds. The Boeing Aircraft Company is using aluminum-alloy-balsa sandwich-construction flooring and aluminum-alloy-plastic-honeycomb interior paneling and partitioning in its model 377 commercial passenger aircraft. Aluminum-alloy-faced plastic-honeycomb sandwich construction is also being used by the Glenn L. Martin Company for sections of flooring, doors, and other parts of aircraft.

The U. S. Air Force, Air Matériel Command, has successfully static-tested a BT-15 airplane fuselage made with glass-fabric-base plastic faces and balsa core and also a similar fuselage made with glass-fabric-base plastic-honeycomb core instead of balsa. Both types of fuselage were also installed in aircraft and successfully flown for many months.

Plastic-faced sandwich construction, mainly with cellular hard-synthetic-rubber core, was successfully used in thousands of aircraft radar-antenna housings, or radomes, in service during the war on com-

bat, transport, and reconnaissance aircraft. Future high-speed aircraft and missiles, as well as transport aircraft, will make increasing use of plastic sandwich construction as both radio- and radar-antenna housings which will be integral parts of the structure, as fuselage, wing, or empennage, instead of being parts added as protuberances.

The U. S. Air Force, Air Matériel Command, has also constructed a wing for the AT6 airplane of plastic sandwich construction consisting of glass-fabric-base plastic-laminate faces and wrapped cellular cellu-



FIG. 20-25. Plastic Sandwich Construction AT6 Wing.

lose acetate core which has been successfully static-tested. This wing is shown in Fig. 20-25.

Aircraft propellers are being experimentally tested which consist of thin sheet steel filled with a low-density cellular core such as cellular hard synthetic rubber for support of the thin sheet. Another possibility is the use of glass-fabric-base plastic low-pressure-laminated onto a balsa core.

Applications of sandwich construction other than in aircraft are boats, truck and trailer bodies, bulkheads and partitions for railroad cars, doors and furniture, shipping containers, and housing. Experimental houses have been built with sandwich-construction walls and roofs using aluminum sheet and paper-base plastic-honeycomb core about 2 in. thick for wall and 3 in. thick for the roof. A 5-room house weighed only 1 ton compared to 40 tons for conventional construction.<sup>61, 68</sup> Table 20-8 lists the references describing applications of sandwich construction.\*

\* See Chapter 18 for a further discussion of building-board sandwiches.

## SANDWICH CONSTRUCTION FOR RADAR-ANTENNA HOUSINGS

General information on the applications and basic principles of radar is now widely available as a result of voluminous publicity. In spite of the fact that the subject of radar-antenna housings (or "radomes") is not generally included in the usual discussion of radar, the housing is an important and critical part of the entire radar installation and must be considered electrically along with all the other components of the system.

The primary reasons for the use of a housing for the antenna are to protect the latter from wind and weather and, on aircraft, to streamline the installation aerodynamically and support the air loads. Another reason is concealment of the installation. Since the housing must transmit the radiated energy which is in the form of very short-wavelength radio waves, it must be made of nonmetallic material, but the restrictions do not end there. Returning to the basic radar principles, a narrow beam of short-wavelength radio waves in the form of short pulses is transmitted in a given direction. This train of pulses is reflected back by any solid target it meets and is received again by the radar antenna. The radar set measures the time interval between the transmission and reception, and, since the velocity of the radiation is the same as that of light, the distance between the antenna and the target, or the range, is automatically determined. Also the direction or the bearing of the target is determined from the direction of the beam. For accuracy in the bearing determination, a narrow beam is required and, therefore, very short-wavelength "microwave" radiation.

The performance of the radar set as outlined is definitely affected by the antenna housing, as follows:

1. Reflected energy from the housing is directed back into the antenna and, if appreciable, causes serious distortion and other difficulties.
2. The distance which can be scanned efficiently depends on the power transmitted, which depends, in turn, on the relative amounts of energy reflected from the antenna housing, absorbed in it, or transmitted through it.

For normal incidence of the radiation on the antenna housing, a double-wall housing can be designed such that the reflection from one face is partially or completely canceled by that from the other, so that little or no energy is reflected back into the antenna. In order to control the required spacing between the two walls or faces, obtain sufficient strength and rigidity, and render the construction practicable, a low-density core material is employed to separate the two faces and is

bonded to them. The core material, being principally air, generally has a dielectric constant close to that of air. Thus it is seen that a light-weight structure can be obtained for the application which is excellent from both mechanical and electrical considerations.

For normal incidence, the correct value of the core thickness required to result in zero reflection can be calculated if the following factors are known or chosen:

1. Thickness of faces.
2. Dielectric constants of face and core.
3. Wavelength of radiation.

Therefore, thick faces of material of relatively high dielectric constant can be used if desired and if the loss due to absorption is not too high.

In general, however, the antenna housings are of a streamlined shape, such as part of the fuselage of an airplane, and the angle of incidence may vary over the area from normal to  $70^\circ$  or more away from normal. To obtain good transmission in such cases it is generally necessary to have very thin faces and very close tolerances on the core and face thicknesses. The lower the dielectric constants of the core and face materials, however, the less close these tolerances must be for given percentage transmission and angles of incidence.

For low absorption of energy in the material of the antenna housings, the face and core materials must have the lowest possible loss tangent and dielectric-constant values. The materials must also have low water and water-vapor-absorption properties, because presence of a substantial amount of water in the material increases the loss tangent and dielectric constant and the absorption of radiated energy in the material.

Sandwich constructions which have been successfully used for aircraft radar-antenna housings (or "radomes") are low-pressure bag-molded glass-fabric-base polyester thermosetting plastic faces bonded to cellular hard synthetic-rubber core or to glass-fabric-base plastic-honeycomb material. Core-material densities are generally confined within the range of 8 to 12 pcf. It is noteworthy that the dielectric constant and loss tangent of the honeycomb core as such cannot be determined as for cellular hard synthetic rubber and other homogeneous materials, but the honeycomb core performs efficiently in the electrical sandwich, evidently because the honeycomb core also is principally air.

As has been mentioned, increasing use will be made of plastic sandwich-construction radar- and also radio-antenna housings in aircraft and missiles as part of the structure for aerodynamic reasons. This

increases the importance of the structural aspects. In connection with radio-antenna housings, the advantages of sandwich construction over straight sheet-laminated plastic are principally structural, instead of electrical, because of the larger wavelengths employed and less critical requirements.

#### SANDWICH-CONSTRUCTION FABRICATION

It is essential in structural-sandwich construction to obtain a good bond between the faces and the core in order that the full strength of the sandwich be developed. Production of a good bond is one of the principal problems in sandwich-construction fabrication.

For metal-faced sandwich construction with balsa, honeycomb, or low-density plastic cores, two general types of bonding procedures are in use. One consists of applying a synthetic-resin hot-setting metal-to-metal-type structural adhesive to the metal face as a primer and curing this adhesive. The face is then glued to the core, employing a hot-setting or a cold-setting synthetic-resin adhesive of the types used for wood gluing \* (phenolic, resorcinol, and urea), to bond the primed side of the metal face to the core. The other procedure consists of using a one-step-process hot-setting metal-to-metal-type structural adhesive for direct bonding of the face to core. This adhesive may be applied to both the face and core before assembly and cure. In the case of honeycomb cores, application to both is usual in order to obtain sufficient resin to form fillets around the honeycomb cell walls, which fillets are necessary to produce a good bond.

In either method it may be necessary to precure to some extent the adhesives used after application and before assembly in order to eliminate as much of the volatiles as possible and thus to avoid entrapment in the cores. Sometimes also, a thin resin film is cured onto the balsa or low-density plastic cores before the gluing and assembly operations to prevent too much penetration of liquid-resin adhesives. Consideration of these factors must also be given in the case of plywood and plastic faces.

For curved parts, the metal faces are formed first, the core is formed or machined, and the assembly bonded together by bag molding.†

Metal-honeycomb core may also be bonded to metal faces as previously described. There is the possibility, however, of an all-metal sandwich construction employing metal-honeycomb core. If the honeycomb core is made by joining corrugated sheets together by

\* See Chapter 2 for an extended discussion of adhesives.

† See Chapter 22 for an extended discussion of molding procedures.

welding or brazing instead of gluing, the core might also be joined to the metal faces by welding or brazing.

Plywood faces may be bonded to the various core materials (except metal honeycomb) with wood adhesives such as phenolic. Usual bag-molding procedures may be used. However, it is noted in reference 101 that, in the production of the Mosquito fuselage (plywood-faced balsa), flexible steel-band clamps were used to give the required pressure for bonding.

Plastic-faced sandwich constructions may be made by various procedures. Low-pressure laminating resins are used, usually of the polyester thermosetting type, but phenolic resins and thermoplastic resin have also been used. Layers of glass fabric or other filler material are impregnated with the resin. In the case of the polyester resins, the layers of impregnated fabric, being 100 per cent reactive, may be laid up in the mold in the wet uncured condition, the previously formed core material then put into place, and then the layer of impregnated material for the other face put on. The assembly is then bag-molded, curing of the faces and bonding to the core occurring simultaneously. A similar procedure may be followed for the case of phenolic-type and thermoplastic-type laminating resins, except that they are impregnated from solution and are laid up dry after drying to remove solvents.

Plastic faces may also be molded to shape and cured separately and glued to the core material, hot-setting adhesives or the laminating resin being used as an adhesive. Also, in some cases it is advantageous to premold one face, glue the core to it, and wet-laminate on the other face. Another possibility is postforming of cured sheet to shape and gluing this to the core.

It is also possible to lay up plastic faces against a male mold and a female matching mold, foam a resinous core into place between the two faces, and cure the assembly. If partially cured and expanded cellular hard synthetic rubber is used similarly between the two faces, the rubber expands against the faces, cures, and provides pressure against the faces as the latter cure also. There are many variations of the afore-mentioned procedures. It should be noted that bag molding need not necessarily be done in an autoclave. Pressure due to evacuation of the bag only may be used and the assembly placed in an oven for cure. Heated molds may be used, employing steam coils or other means of heating. Also a two-part mold can be utilized with the material being heated from the mold side and from the bag side also by means of steam coils in the mold and steam in the space between the bag and the other mold part.

As has been discussed previously, the emphasis in fabrication should be on close control of materials and of all steps in processing and fabrication, because inspection of the finished product as to quality of bond, completeness of cure, and similar factors is difficult.

#### SANDWICH-CONSTRUCTION DESIGN \*

The usual buckling and other design criteria equations applicable to metals and other homogeneous materials cannot, in general, be used directly for sandwich construction, owing to certain inapplicable assumptions in their derivations. These derivations must be modified, and, therefore, the resulting equations are different because of these three general conditions:

- (a) Sandwich construction is a composite of different materials.
- (b) Either the face or core material or both may be anisotropic.
- (c) The core material is thick relative to the faces and generally has a relatively low modulus of rigidity in shear, resulting generally in high core-shear deformation which cannot be neglected, and the elastic moduli, tensile, compressive, and shear strengths of the core are also relatively low and may also limit the performance of the sandwich construction in some cases.

Of course, the same fundamental physical considerations apply so that, in general, the derived equations reduce to the simpler ones used for metals in the limiting case when the additional restrictive conditions applied are deleted.

It should be noted that the modifications taking into account the first two factors, those of composite construction and anisotropy, have already been made for plywood and wood construction. The theoretical results are, of course, applicable for materials other than wood, such as plastic laminates, and are summarized in ANC-18, Army-Navy-Civil bulletin, Design of Wood Aircraft Structures. The theoretical work and corroborative empirical tests were accomplished by the staff of the Forest Products Laboratory of the U. S. Department of Agriculture, Madison, Wis., under the direction of the Army-Navy-Civil Committee on Design Criteria of the Aeronautical Board, and sponsored by the U. S. Air Force, Air Matériel Command, and Navy Department Bureau of Aeronautics. Details are given in available Forest Products Laboratory reports.

The Forest Products Laboratory has been and is now working on a program of modifying the design criteria derived for wood and plywood

\* See also Chapter 1 for a discussion of sandwich design.

to be applicable to sandwich construction, taking into account the third factor previously outlined. This involves a relatively difficult and comprehensive theoretical undertaking which cannot be completed in a short time, but empirical tests are also being made to check the equations derived and, where necessary, will serve for design data in the interim. A series of Forest Products Laboratory reports is being prepared covering this work, and a bulletin, ANC23, will be issued later summarizing design criteria for sandwich construction. A number of reports have been issued already, as given in references 16, 23, 39, 83, 85, 91, 93, 97. Theoretical work on design criteria and empirical tests of sandwich construction have also been accomplished by the British Royal Aeronautical Establishment, the U. S. Air Force, the Navy Bureau of Aeronautics, and various aircraft manufacturers. Available information from these sources are given in references listed in the bibliography, see Table 20-8. Only a general qualitative discussion of sandwich-construction design is included here. The original references should be referred to for the design equations.

It is assumed that the size, shape, edge conditions, and load to be carried by the part of the structure under consideration are known. Also, it is assumed that the materials to be used (or employed in a trial calculation) and their properties are known. A specific example would be a curved panel, 20 in. wide, 30 in. long in direction of load, 40 in. radius of curvature, clamped edge and end conditions, load 40,000 lb in compression longitudinally, aluminum-alloy faces, balsa core with the grain perpendicular to the faces. The general procedure to be followed, for this and other cases, as shear or combined loading, flat or curved panels, is:

1. Given the compressive yield strength of the face material and the width of the panel, the thickness of the material required to carry the load can be calculated, if it is assumed that the material will be stressed to its yield strength before the panel fails. This value divided by two will be the thickness of each face.

From the properties of the face and core materials, the edge conditions, size of panel, and the load, it is possible to calculate the thickness of the core material required so that the buckling load of the sandwich equals the design load. This includes consideration of possibility of failure of the panel by crimping or offset accompanied by shear failure of core. However, this latter type of failure is usually not critical and occurs after buckling.

3. This calculated spacing thickness is increased somewhat by calculating a correction for the factor of shear deformation of the core.



TABLE 20-9. COMPRESSIVE ULTIMATE STRENGTH OF SANDWICH CONSTRUCTIONS

Short Column or Crushing Strength, Edges Unsupported, Ends Clamped  
Air Materiel Command and Forests Products Laboratory Data

1 Type of Face Material	2 Average Face Thickness, in.	3 Total Sandwich Thickness, in.	4 Weight of Sandwich, psf	5 Ult. Strength, lb/in. Width	6 Specific Strength, Col. 5/Col. 4	7 Nominal Stress in Faces,† psi, Col. 5/2 × Col. 2
<i>Core: Cellular Phenolic Resin</i>						
5 plies 112 *	0.015	0.60	1.22	614	504	18,400
<i>Core: Low-Density Fiberboard, Phenolic Resin Binder</i>						
5 plies 112	0.015	0.43	0.98	515	528	17,400
<i>Core: Cellular Urea Formaldehyde Resin</i>						
5 plies 112	0.015	0.46	1.21	263	233	9,400
<i>Core: Foamed Calcium Alginate</i>						
5 plies 112	0.015	0.53	0.72	330	465	11,000
<i>Core: Honeycomb Glass Cloth</i>						
3 plies 112	{ 0.010	0.27	0.45	262	582	13,100
	{ 0.010	0.50	0.56	253	452	12,700
	{ 0.010	0.76	0.89	237	266	11,900
	{ 0.010	0.99	0.98	249	254	12,500
5 plies 112	{ 0.015	0.52	0.64	612	956	20,400
	{ 0.017	0.24	0.45	490	1,089	14,400
6 plies 112	{ 0.017	0.50	0.60	436	726	12,800
	{ 0.017	0.76	0.76	402	529	11,800
	{ 0.017	0.99	0.86	429	499	12,600
<i>Core: Extruded Cellular Cellulose Acetate</i>						
3 plies 112	{ 0.010	0.27	0.30	239	796	11,900
	{ 0.010	0.51	0.43	272	633	13,600
	{ 0.010	0.75	0.60	377	628	18,800
	{ 0.010	1.00	0.80	206	257	10,300
5 plies 112	{ 0.015	0.46	0.67	730	1,077	24,300
	{ 0.019	0.28	0.46	587	1,276	15,400
6 plies 112	{ 0.019	0.53	0.62	773	1,247	20,300
	{ 0.019	0.76	0.83	653	787	17,000
	{ 0.019	1.02	1.01	671	664	17,600
7 plies 112	0.021	0.51	0.67	870	1,292	20,700
9 plies 112	{ 0.027	0.52	0.78	1,002	1,279	18,500
	{ 0.030	0.30	0.69	1,271	1,842	21,200
10 plies 112	{ 0.030	0.55	0.81	1,341	1,656	22,400
	{ 0.030	0.77	1.02	1,177	1,154	19,600
	{ 0.030	1.04	1.23	1,231	1,001	20,500
12 plies 112	0.036	0.60	0.94	1,599	1,706	22,200
14 plies 112	{ 0.042	0.60	1.27	2,265	2,180	32,900
	{ 0.044	0.34	0.98	1,708	1,743	19,300
16 plies 112	{ 0.044	0.58	1.13	1,718	1,520	19,400
	{ 0.044	0.83	1.38	2,165	1,569	24,500
	{ 0.044	1.08	1.54	2,264	1,470	25,700
14 plies 108	0.028	0.57	0.99	1,834	1,856	32,200
6 plies 128	{ 0.042	0.53	1.23	1,206	983	15,100
	{ 0.005	0.25	0.33	213	645	21,300
24 SH †	{ 0.005	0.50	0.49	244	498	24,400
	{ 0.005	0.73	0.68	264	433	29,400
	{ 0.005	0.98	0.80	284	355	28,400
	{ 0.0125	0.28	0.61	1,111	1,821	44,400
24 ST Alclad	{ 0.0125	0.51	0.79	1,095	1,386	43,800
	{ 0.0125	0.78	0.98	972	992	38,800
	{ 0.0125	1.02	1.13	1,107	980	44,300
	{ 0.0125	2.55	2.25	819	364	32,700
	{ 0.0185	0.28	0.80	1,565	1,956	27,400
	{ 0.0185	0.55	0.99	1,454	1,469	25,500
	{ 0.0185	0.78	1.20	1,446	1,205	25,300
	{ 0.0185	1.03	1.33	1,874	1,409	32,800

TABLE 20-9. COMPRESSIVE ULTIMATE STRENGTH OF SANDWICH CONSTRUCTIONS (Continued)

Short Column or Crushing Strength, Edges Unsupported, Ends Clamped  
Air Materiel Command and Forest Products Laboratory Data

1 Type of Face Material	2 Average Face Thickness, in.	3 Total Sandwich Thickness, in.	4 Weight of Sandwich, pcf	5 Ult. Strength, lb/in. Width	6 Specific Strength, Col. 5/Col. 4	7 Nominal Stress in Faces, † psi, Col. 5/2 × Col. 2
<i>Core: Extruded Cellular Cellulose Acetate (Continued)</i>						
24 ST Alclad	{ 0.032	0.31	1.10	2,281	2,074	35,800
	{ 0.032	0.56	1.19	2,244	1,886	35,000
	{ 0.032	0.89	1.42	2,054	1,446	32,000
	{ 0.032	1.04	1.54	2,505	1,627	39,100
<i>Core: Cellular Hard Synthetic Rubber</i>						
3 plies 112	{ 0.010	0.27	0.32	223	697	11,200
	{ 0.010	0.51	0.45	199	442	9,950
	{ 0.010	0.79	0.65	135	208	6,750
	{ 0.010	1.02	0.70	177	253	8,850
6 plies 112	{ 0.019	0.27	0.47	659	1,402	17,300
	{ 0.019	0.54	0.67	543	810	14,300
	{ 0.019	0.82	0.79	808	770	13,300
	{ 0.019	1.04	0.93	685	736	18,000
10 plies 112	{ 0.030	0.31	0.69	1,119	1,622	18,600
	{ 0.030	0.57	0.87	990	1,138	16,500
	{ 0.030	0.83	0.98	1,136	1,159	18,900
	{ 0.030	0.97	1.16	1,271	1,096	21,200
24 SH	{ 0.005	0.27	0.39	278	713	27,800
	{ 0.005	0.50	0.52	329	633	32,900
	{ 0.005	0.77	0.68	380	559	38,000
	{ 0.005	1.02	0.90	459	510	45,900
24 ST Alclad	{ 0.0125	0.30	0.68	1,013	1,440	40,600
	{ 0.0125	0.54	0.85	1,175	1,382	47,000
	{ 0.0125	0.79	0.95	994	1,046	35,800
	{ 0.0125	1.05	1.17	990	846	39,600
	{ 0.0125	2.41	2.24	1,073	479	42,900
	{ 0.0185	0.31	0.83	1,213	1,461	32,800
	{ 0.0185	0.54	0.94	1,549	1,648	41,900
	{ 0.0185	0.80	1.10	1,440	1,309	30,800
	{ 0.0185	1.05	1.31	1,473	1,124	31,700
	{ 0.032	0.33	1.24	2,156	1,739	33,700
	{ 0.032	0.58	1.40	2,096	1,497	32,800
	{ 0.032	0.83	1.54	1,783	1,158	27,800
	{ 0.032	1.08	1.72	1,866	1,085	29,100
<i>Core: Balsa, Grain Parallel to Faces</i>						
5 plies 112	{ 0.015	0.28	0.48	777	1,608	.....
	{ 0.015	0.53	0.61	1,085	1,759	.....
7 plies 112	{ 0.021	0.29	0.58	854	1,481	.....
	{ 0.021	0.54	0.68	1,074	1,594	.....
9 plies 112	{ 0.027	0.30	0.71	1,283	1,797	.....
	{ 0.027	0.55	0.82	1,491	1,905	.....
24 ST Alclad	{ 0.014	0.28	0.65	983	1,520	.....
	{ 0.014	0.53	0.85	1,222	1,443	.....
	{ 0.014	0.78	1.05	1,350	1,293	.....
	{ 0.020	0.29	0.87	1,467	1,685	.....
	{ 0.020	0.54	0.97	1,821	1,886	.....
	{ 0.020	0.79	1.16	1,898	1,737	.....
	{ 0.032	0.31	1.19	2,523	2,117	.....
	{ 0.032	0.56	1.33	2,973	2,230	.....
	{ 0.032	0.56	1.48	3,352	2,265	.....

TABLE 20-9. COMPRESSIVE ULTIMATE STRENGTH OF SANDWICH CONSTRUCTIONS (Continued)

Short Column or Crushing Strength, Edges Unsupported, Ends Clamped  
Air Materiel Command and Forest Products Laboratory Data

1 Type of Face Material	2 Average Face Thickness, in.	3 Total Sandwich Thickness, in.	4 Weight of Sandwich, pcf	5 Ult. Strength, lb/in. Width	6 Specific Strength, Col. 5/Col. 4	7 Nominal Stress in Faces, † psi, Col. 5/2 X Col. 2
<i>Core: Balsa, Grain Perpendicular to Faces</i>						
2 plies 112	0.009	0.28	0.55	349	635	19,400
	0.009	0.52	0.79	362	458	20,100
	0.009	0.76	1.11	311	280	17,300
	0.009	1.02	1.04	276	265	15,300
4 plies 112	0.016	0.29	0.64	677	1,058	21,200
	0.016	0.53	0.81	583	720	15,100
	0.016	0.77	1.23	580	471	18,100
	0.016	1.02	1.22	526	431	16,400
5 plies 112	0.015	0.28	0.56	630	1,133	21,000
	0.015	0.53	0.71	608	854	20,300
7 plies 112	0.021	0.29	0.61	877	1,427	16,100
	0.021	0.54	0.81	632	786	15,100
8 plies 112	0.032	0.32	0.87	1,308	1,503	20,400
	0.032	0.56	1.12	1,360	1,214	21,200
	0.032	0.81	1.58	1,442	912	22,500
	0.032	1.05	1.59	1,180	742	18,400
9 plies 112	0.027	0.30	0.69	986	1,425	18,300
	0.027	0.55	0.82	984	1,207	22,400
16 plies 112	0.044	0.34	1.13	1,918	1,697	21,800
	0.044	0.59	1.12	1,837	1,640	20,900
	0.044	0.84	1.23	2,062	1,676	23,400
	0.044	1.08	1.47	2,062	1,403	23,400
24 SH	0.005	0.26	0.35	362	1,034	36,200
	0.005	0.51	0.46	402	874	40,200
	0.005	0.77	0.60	282	470	28,200
	0.005	1.02	0.65	270	415	27,000
	0.0125	0.28	0.66	1,173	1,777	46,900
	0.0125	0.53	0.80	1,168	1,460	46,700
	0.0125	0.65	0.76	919	1,209	36,700
	0.0125	0.78	0.93	1,081	1,162	43,200
	0.0125	1.03	1.33	1,059	796	42,300
	0.0125	1.27	1.12	839	749	13,600
	0.0125	1.87	1.31	594	453	23,700
	0.0125	2.47	1.70	478	281	14,100
	0.0185	0.30	0.83	2,166	2,610	58,600
	0.0185	0.54	1.00	2,197	2,197	59,300
	0.0185	0.79	1.22	1,914	1,570	51,700
	0.0185	1.04	1.11	1,641	1,480	44,400
24 ST Alclad	0.020	0.29	0.93	2,152	2,337	53,800
	0.020	0.54	1.01	2,172	2,133	54,300
	0.020	0.75	1.13	2,445	2,087	61,100
	0.032	0.33	1.20	3,178	2,650	49,700
	0.032	0.47	1.24	3,192	2,570	49,900
	0.032	0.82	1.43	3,856	2,700	60,200
	0.032	1.07	1.56	4,184	2,680	65,200

\* Low-pressure polyester plastic laminate made with Fiberglas fabric 112 (0.003 in. nominal thickness).

† Aluminum-alloy sheet.

‡ Neglecting stress in core, which factor is not large except for balsa with grain parallel to faces. Actual stress in faces is more closely approximated by

$$S = \frac{\text{ultimate load per inch}}{2f + \frac{E_c}{E_f} C}$$

where  $f$  = face thickness $c$  = core thickness $E_c$  = modulus of elasticity of core $E_f$  = modulus of elasticity of face

4. The panel is then examined for the loads at which (a) face wrinkling and (b) flatwise tensile failure at the glue line or in the core material occurs. If either of these loads is below the buckling load, then the panel must be modified by employing thicker or stronger faces or core. Ordinarily, the choice could be thicker faces to prevent wrinkling and stronger core or bonding to prevent tensile failure.

TABLE 20-10. STIFFNESS FACTORS FOR SOME SANDWICH CONSTRUCTIONS \*

Face Thickness, In.	Over-all Thickness, In.	Weight, psf	Bending Stiffness, $EI$ , <sup>†</sup> lb-in. <sup>2</sup> /in. Width	Shear Stiffness, lb-in. <sup>2</sup> /in. Width	Compressive Ultimate Strength, lb/in. Width
<i>24 ST Alclad Aluminum-Alloy Faces, Balsa Core, Grain Perpendicular to Faces</i>					
0.005 ‡	0.43	0.44	5400	1700	465
0.012	0.27	0.61	4500	1470	1170
0.020	0.23	0.75	4400	1430	1780
0.032	0.26	1.15	7900	2760	2440
<i>Glass-Fabric Plastic Laminate (Fiberglas Fabric 112)</i>					
0.010 §	0.45	0.41	2300	230	197
0.019	0.28	0.49	1700	290	590
0.030 ¶	0.24	0.80	1530	287	1370
0.046 **	0.28	0.98	3160	593	1860

\* Reference 85 data.

|| 6 plies 112.

† Corrected for shear deformations.

¶ 8 plies 112.

‡ 24 SH aluminum alloy.

\*\* 16 plies 112.

§ 3 plies 112.

If the face and core thicknesses and materials are fixed, and it is desired to calculate the maximum load, the lowest load as calculated on the following bases would be taken: (1) yield or ultimate strength of faces, (2) buckling of panel as a whole (including crimping failure of panel with shear failure of core), (3) wrinkling of faces, (4) tensile failure of bond or core, (5) if honeycomb core material is being used, the cells may be large enough with respect to face thickness that buckling of the faces into the cells may occur, so that this buckling criterion must also be investigated.

Deflections must also be investigated in design. When sandwich construction panels are subjected to flexural loads, the deflections due to shear usually cannot be neglected as is ordinarily done. For simple beam bending, for example, the effective stiffness factor  $EI$  will increase with the span length because the shear decreases with span length.

TABLE 20-11. BUCKLING AND ULTIMATE STRENGTH IN COMPRESSION OF FLAT SANDWICH-CONSTRUCTION PANELS \*

All Edges Simply Supported

Core: Balsa, Grain Perpendicular to Faces

Face Thickness, in.	Over-all Thickness, in.	Weight, psf	Length and Width, in.	Critical (Buckling) Load, lb/in. Width	Ultimate Load, lb/in. Width
<i>Aluminum Alloy, 24 ST Alclad faces †</i>					
0.012	0.27	0.61	20.5	376	544
			18.5	432	550
			15.5	524	676
			13.5	656	692
			10.5	842	863
			9.5	821	821
			8.5	980	980
<i>Aluminum Alloy, 24 ST Alclad Faces ‡</i>					
0.020	0.23	0.75	23.5	284	560
			14.5	716	908
			13.5	700	831
			11.3	1145	1210
			10.3	1160	1185
			9.4	1200	1234
			8.5	1220	1265
<i>Glass-Fabric-Base Plastic Laminate (8 Plies 112 Fiberglas Fabric) §</i>					
0.030	0.24	0.80	19.5	152	400
			13.5	289	552
			11.5	460	595
			9.5	566	685
			8.5	666	733
			7.5	741	748
			6.5	1139	1139
<i>Glass-Fabric-Base Plastic Laminate (16 Plies 112 Fiberglas fabric)   </i>					
0.046	0.28	0.98	23.5	192	361
			17.5	291	685
			14.5	454	550
			12.5	563	838
			10.5	778	991
			9.5	962	1005
			8.5	1100	1105

\* Stiffness and compressive strength properties given in Table 20-10. Data from reference 85.

† Compressive yield strength 44,000 psi.

§ Compressive strength, 24,000 psi.

‡ Compressive yield strength 42,000 psi.

|| Compressive strength, 23,000 psi.

In addition to fundamental strength and stiffness properties, designs must take into account factors such as fatigue, creep, handling loads, impact, and other factors, as in flooring, such as rolling loads and concentrated loads. Most of these factors are at present not very susceptible to analytical treatment in the case of sandwich construction.

TABLE 20-12. BENDING TEST DATA

Glass-Fabric-Base Plastic-Faced Sandwich Constructions  
Fiberglas 112 Fabric; 12-in.-Width Specimens, 28-in. Span, Loaded at Third Points

No. of Plies	Face Thickness, in.	Total Thickness, in.	Weight, psf	Ultimate Strength, lb/in. Width	Stiffness Factor, $EI$ , lb-in. <sup>2</sup> /in. Width
<i>Core: Balsa, Grain Perpendicular to Faces</i>					
9	0.027	0.33	0.77	370	3,600
7	0.021	0.46	0.76	420	5,050
12	0.036	0.56	1.22	1,270	12,600
12	0.036	0.79	1.28	1,625	25,300
12	0.036	1.04	1.47	1,665	45,100
<i>Core: Balsa, Grain Parallel to Faces and Span</i>					
9	0.027	0.29	0.71	385	3,200
7	0.021	0.42	0.63	300	5,350
6	0.018	0.48	0.62	465	7,600
<i>Core: Balsa, Grain Parallel to Faces and Perpendicular to Span</i>					
9	0.027	0.29	0.68	210	2,350
7	0.021	0.42	0.60	225	3,750
6	0.018	0.48	0.73	300	4,350
<i>Core: Extruded Cellular Cellulose Acetate</i>					
9	0.027	0.54	1.00	860	10,400
<i>Core: Cellular Hard Synthetic Rubber</i>					
6	0.018	0.55	0.86	500	6,600
<i>Core: Glass-Fabric-Base Plastic Honeycomb</i>					
6	0.018	0.51	0.62	370	5,000

Because of the large number of variables involved, it is, of course, not possible to give here sufficient empirical data for design use. However, data are given in Tables 20-9 to 20-12, inclusive, which illustrate typical effects of variation of skin and core thicknesses and materials on compressive strengths, stiffness factors, and buckling strengths of some sandwich constructions. All the plastic-faced sandwich-construction data refer to faces of glass-fabric-base plastic laminate made with a low-pressure polyester laminating resin.

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# CHAPTER 21

## Rubber Laminates

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### NATURAL AND MAN-MADE RUBBERS

Until the early 1940's most rubber products were made from a natural basic hydrocarbon [empirical formula  $(C_5H_8)_x$ ] obtained from such sources as the tree *Hevea brasiliensis*. The Second World War made it necessary to turn to rubber-like raw materials synthesized from various chemicals. These materials are not true synthetic rubbers—as they often are termed—for the basic hydrocarbon of tree rubber never has been duplicated in a laboratory. Therefore, they have, as a group, been named “American-made rubber” or simply “American rubber,” whereas natural tree rubber is generally called “crude rubber.”

### SOME AMERICAN-MADE RUBBERS

Crude rubber is composed of large complex molecules which, by destructive distillation, yield the liquid, isoprene [ $CH_2:CHC(CH_3):CH_2$ ]. Only Nature has been able to build true crude-rubber molecules, but chemists have learned how to polymerize various relatively simple molecules into highly complex ones to produce substances resembling crude rubber. Such synthesized elastic materials may possess some properties that are equivalent to similar properties of crude rubber, some that are inferior, and some that are superior.

Following is a summary of the principal man-made rubbers produced in the United States:

**GR-S Type.** Most nearly like crude rubber, this is a product of the copolymerization of styrene and butadiene. It is not oil-resistant but

\* This chapter is based on material more fully treated in *Engineering with Rubber*, published by the McGraw-Hill Book Company, Inc., and *Rubber as an Engineering Material*, published by the B. F. Goodrich Company.

is used widely in the manufacture of tire casings. It comprised nearly five sixths of the rubber processed during World War II. GR-S-type rubbers include Hycar OS-10 and OS-20, Chemigum B, Butaprene, Nubun, and Ameripol F.

**Nitril Rubber.** Known as GR-A when it was made in Government plants, this material is a copolymer of acrylonitrile and butadiene. Resistance to oils and solvents is excellent, making it useful for fuel and solvent hose, hydraulic-equipment parts, and the like. It is marketed under such names as Ameripol D; Chemigum N-1, N-2, and N-3; Hycar OR-15 and OR-25; Perbunan; and Butaprene N. German Buna N rubber was similar to Nitril.

**Butyl Rubber.** This is made by the copolymerization of isobutylene with small proportion of isoprene or butadiene. Its chief characteristic is its low gas permeability, which is an outstanding property of butyl inner tubes for tires.

**Neoprene.** Various types are produced by polymerization of chloroprene. It has good mechanical properties; is highly resistant to sunlight, heat, aging, and oil; and is used for making machine belts, gaskets, oil hose, and so on.

**Sulfide Rubbers or Thiokols.** Rubbery properties are associated with the higher molecular weights of these condensation products. Articles made from them, such as hose and tank linings, exhibit good resistance to solvents and oils, ozone, and low temperatures.

**Silicone Rubber.** Carbon, oxygen, hydrogen, and silicon are combined to form a material exhibiting unusual heat resistance. It is used in making gaskets, electrical insulation, and similar products.

Other man-made elastomers include polybutene, polyethylene, polyester, cyclized rubbers, and various plastics such as plasticized polyvinyl chloride.

## COMPOUNDING AND VULCANIZATION

These raw rubbers are quite different in appearance and in other properties from the familiar elastic substances commonly called "rubber." The raw rubbers are generally quite plastic, especially when warm; and they have relatively low strength. Various solvents attack them, causing swelling, and often even dissolve them to form cements. The plastic characteristics are essential for the processing, assembling, and forming operations necessary in manufacturing rubber articles, but these generally are not consistent with the strength, heat stability, and elasticity which the finished product must have in order to be

serviceable. For nearly all purposes, the rubber articles, before use, must be given a heat treatment called vulcanization, which decreases the plasticity of the material and makes it stronger, more firm, and less sensitive to the effect of temperature changes. Vulcanization is accomplished by chemical changes which may require incorporation of sulfur, zinc oxide, organic accelerators, or other compounding ingredients in the raw rubber prior to the heat treatment. In addition, compounding ingredients which are not directly involved in the vulcanization reactions, such as carbon black, antioxidants, and many other materials, may be added to the raw rubber to produce desired characteristics. The rubber in finished products, therefore, may have widely different compositions and properties which depend not only on the particular basic rubber material but also on the proportions and properties of the compounding ingredients and the degree of vulcanization. Many rubber products are laminated structures of rubber compounds and other materials such as fabric or metals. These are usually assembled prior to the vulcanization which serves both to change the properties of the rubber and to unite the laminations in a firmly bound composite structure.

#### "HARD" AND "SOFT" RUBBERS

A true hard-rubber compound is one in which a high degree of hardness and rigidity is produced by vulcanization involving the use of 30 to 50 per cent, by weight, of sulfur.

A "soft" rubber compound is one vulcanized with less than 10 per cent sulfur. This includes most of the usual elastic rubbers, although in exceptional cases the actual hardness may, by the inclusion of filler material, be made nearly as great as that of a true hard rubber.

#### PROPERTIES OF RUBBER COMPOUNDS

In the following summary of properties, the reference is to soft vulcanized-rubber compounds unless otherwise stated. Different manufacturers may produce compounds or products identical or very similar in characteristics; but, since it is not customary for them to publish their innumerable compounding formulas, and because analysis to determine the make-up of a compound may be impossible, the precise composition of a specific rubber item often is not disclosed.

**Age Resistance.** It is normal for rubber compounds to oxidize slowly while exposed to air at ordinary temperature. Oxidation is

speeded by additional heat and oxygen (ozone). Chemical antioxidants are mixed with the rubber to retard aging. Hard rubber ages less readily than soft. American rubber compounds are usually superior in aging characteristics.

**Compressibility.** Rubber compounds have practically the same compressibility coefficient as water and thus are virtually noncompressible (excepting sponge rubber). The soft-rubber compressibility curve resembles that of liquids.

**Electrical Properties.\*** The specific inductance capacity at 1000 cycles ranges from 2.32 to 10.9 for gum stocks of crude and American rubber at 70°F (for crude rubber, 2.69). The volume resistivity in ohm-centimeters ranges from  $1 \times 10^9$  to  $1 \times 10^{15}$ . Rubber can be compounded to conduct electricity, in which case the volume resistivity drops below  $1 \times 10^2$  ohm-cm.

**Elongation.** The elongation of soft vulcanized compound may be as great as 1000 per cent of the original length. The elongation of hard rubber ranges generally between 1 and 50 per cent, an elongation above 10 per cent indicating a somewhat soft compound. Rubber is unique because it can return almost to its original length after such extreme stretching.

**Energy Absorption.** The energy-storing ability is about 150 times that of spring-tempered steel. The resilient energy-storing capacity, in foot-pounds per pound, is 95.3 for spring steel and 14,600 for rubber.

**Elasticity.** A distinctive property of vulcanized rubber is its ability to recover from extreme distortion. The recovery is not necessarily complete, for at considerable elongation rubber is not perfectly elastic. If per cent of stretch is plotted against load, the curve representing the stretching cycle will not be the same as that representing the return cycle; the two curves together form a hysteresis loop. The area within the loop represents energy lost in the form of heat resulting from internal friction. In successive cycles, hysteresis becomes less with each stretching and finally reaches a fairly constant value. The behavior of a typical rubber compound in successive stretchings is shown in Fig. 21-1.

At very low elongation, rubber behaves in the manner of steel and conforms to Hooke's law which states that stress is proportional to strain. At greater elongation the law no longer applies. The modulus, or stress for a given elongation of the rubber, can be varied by compounding, becoming greater as pigments are added to the rubber com-

\* As reported by Ball and Maassen.



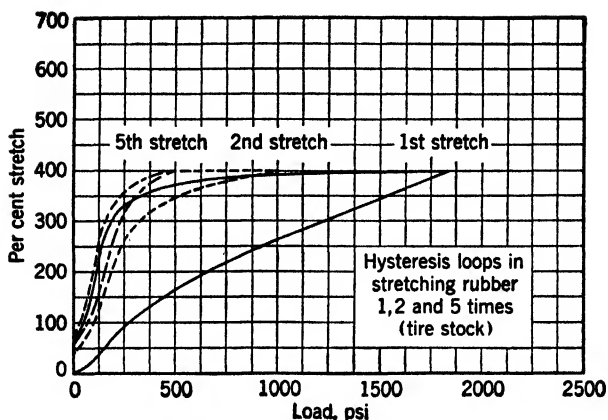


FIG. 21-1. With Constantly Repeated Cycles and a Constant Vibrating Force, the Hysteresis-Loop Areas Become Almost Constant. But for a vibrating force of varying magnitude the loop areas vary and afford a source of variable friction, which is desirable in some instances. The areas of these loops may be varied within wide limits by the recipe or compound of rubber used. Highly pigmented stocks have large hysteresis losses, while stocks approximating pure gum have relatively small losses.

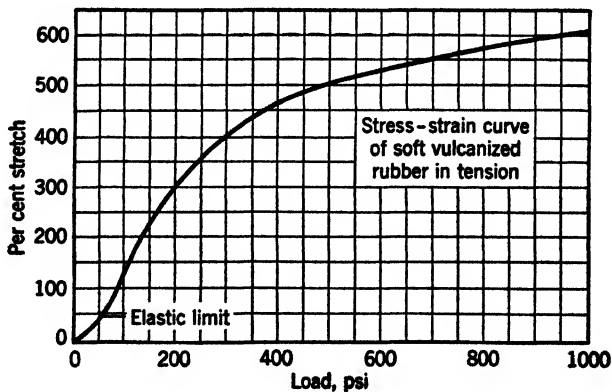


FIG. 21-2. A Study of the Magnified Stress-Strain Curve Discloses That Rubber Does Not Behave According to Hooke's Law Except at Very Low Elongations. Stress is proportional to the strain up to about 50 psi. Within this limit, high-grade soft vulcanized rubber will be almost perfectly elastic under repeated reversals of stress. Computations show this particular stock of Durometer 35 to have a modulus of elasticity of 120, compared with steel, of which the modulus of elasticity is approximately 30,000,000. For absorbing shocks and damping vibrations rubber of a low modulus of elasticity is usually preferred.

position. Figure 21-2 is a stress-strain curve showing how a rubber compound deviates from Hooke's law.

**Expansion, Contraction.** Volumetric changes caused by temperature variations are generally greater for rubber than for metals. Typical values are given in Table 21-1.

TABLE 21-1

Material	Temp. Range, °F	Thermal Coeff. of Exp.
Soft vulcanized-rubber compounds	32-140	0.00011-0.00005
Hard vulcanized-rubber compounds	32-140	0.00004-0.000015
Aluminum	32-212	0.000012
Brass	32-212	0.00001
Glass	32-212	0.000005
Steel	32-212	0.000007

**Friction Characteristics.** The coefficient of friction between soft rubber and dry steel may exceed 1.0, but it is very low when surfaces are wet, the value depending on the hardness of the rubber and the nature of the surfaces. The coefficient between a tire and a dry road is about 0.65. In water-lubricated rubber marine bearings, the coefficient of friction with a shaft speed of 183 sfpm is 0.05 at low speeds, and as low as 0.02 at high speeds.

**Hardness.** Instruments used to measure the static hardness of rubber compounds include: Shore Type A Durometer whose indenter tip, a truncated cone, is pressed against the rubber by a spring capable of exerting a maximum load of approximately 2 lb, used to measure soft-rubber stocks; Type C Durometer, having a maximum 12-lb indenter load, used for stiffer compounds; Type D Durometer, with a needle-point indenter, used for hard rubber; Pusey & Jones Plastometer, a dead-weight device having a ball-shaped indenter  $\frac{1}{8}$  in. in diameter for average compounds,  $\frac{1}{4}$  in. for very soft rubbers; and the ASTM Hardness Tester, another dead-weight device, having an indenter with a ball point 0.0938 in. in diameter.

On the Durometer A scale, glass gives a reading of 100. Soft-rubber compounds having preferred properties usually fall between 50 and 70 points on this scale. Crude rubber, nitril, and GR-S can be made to a hardness of 100, whereas the top for butyl is around 75, and for neoprene and Thiokol FA it is 90 and 80, respectively. Butyl compounds may be made as low as 15 Durometer A, while crude rubber vulcanizates range down to 20. The softest GR-S is about 35.

**Heat Resistance.** Vulcanized-crude-rubber compounds are normally limited in use to temperatures of 150° to 200°F, although under some

conditions they will withstand 300°. Some American-rubber compounds will remain serviceable at temperatures around 450°F.

**Light Resistance.** Crude, GR-S, and nitril-rubber compounds under tension will crack when exposed to light of sunlight quality. The cracking is actually caused by ozone created by short-wavelength radiation acting on atmospheric oxygen. Rubber can be compounded to resist light or ozone action. Sunlight discolors hard rubber a little and reduces its surface electrical resistivity.

**Odor.** A rubber compound having an unpleasant odor usually contains some compound ingredient, other than rubber, that is to blame. Odor can be reduced by careful compounding. Often synthetic-rubber compounds can be identified by their odor. GR-S has a mild inoffensive aroma that is characteristic. Nitril rubbers similarly have a distinctive inoffensive odor. Neoprene has a somewhat more noticeable odor, whereas a sulfide rubber (Thiokol) may exhibit a decided odor. Unvulcanized butyl rubber has almost no odor, although compounding ingredients may contribute some.

**Permeability to Gases.** An important property of most rubber compounds is the low rate of penetration of air and other gases through them. Age and composition of the rubber have an important effect on permeability. Permeability increases with pressure and temperature and is inversely proportional to rubber thickness. Thiokol FA and butyl compounds exhibit very low rates of permeation by air, hydrogen, helium, and carbon dioxide, in comparison with crude and GR-S compounds. A butyl inner tube will lose air by permeation only about 10 per cent as rapidly as will a natural-rubber tube.

**Solubility.** Crude rubber is converted into a solution by dispersion of the solvent through it, which causes it to swell, become jelly-like, and then break down into a viscous fluid. Common rubber solvents are: crude rubber—nonleaded gasoline, benzol, solvent naphtha, chloroform, carbon bisulfide, carbon tetrachloride, turpentine; for nitril rubber—methyl-ethyl ketone; for GR-S, butyl—gasoline; for neoprene—isopropyl acetate.

**Specific Heat.** Thermal properties of rubber compounds can be controlled by varying the quantity and quality of the compounding ingredients. In the temperature range 60–212°F, soft rubber has a value of 0.48 and hard rubber a value of 0.33.

**Strength.** Tensile strength, based on the original cross section, ranges from 300 to 4500 psi for soft-rubber stocks, and from about 1000 to 10,000 psi for hard rubber. Comparative maximum tensile strengths of carbon-black stocks of various rubbers at room temperature, taking

TABLE 21-2. CHEMICAL RESISTANCE OF LINING MATERIALS

Based on maximum temperature limits of 150°F unless otherwise stated. At temperatures from 150° to 210°F the effects of oxidation, diffusion, and absorption are accelerated, and the life is shortened but in many cases is sufficient to justify the use of these linings, especially if oversheathed with suitable brick sheathing. Unless specific maximums are given, chemical concentrations are for any values up to saturation at atmospheric pressure. For low concentrations, from 0 to 5 per cent, it is generally preferable to use hard or semihard types of lining to prevent water soaking and surface effect.

G = good  
F = fair  
P = poor  
IL = information lacking

	Rubber	Plasticized Polyvinyl Chloride
Acetaldehyde	P	P
Acetate solvents, crude	P	P
pure	P	P
Acetic acid, glacial <sup>1</sup>	G	P
Acetic anhydride	G	P
Acetic acid vapors	G	P
Acetone	G	P
Acid mine waters	G	G
Alcohol, methyl <sup>2</sup>	G	F
ethyl	G	F
propyl	G	F
isopropyl	G	F
butyl	G	F
isobutyl	G	F
amyl	G	F
Alum, ammonium	G	G
chrome	G	G
potassium	G	G
sodium	G	G
Aluminum acetate	G	
Aluminum bromide	G	G
Aluminum chloride	G	G
Aluminum fluoride	G	F
Aluminum nitrate	G	G
Aluminum sulfate	G	G
Ammonium chloride	G	G
Ammonium hydroxide <sup>3</sup>	G	F
Ammonium persulfate	G	
Ammonium sulfate	G	G
Arsenic acid	G	G
Aniline hydrochloride	G	
Battery acid (sulfuric)	G	G
Beet sugar liquors	G	
Beer <sup>1</sup>	G	G
“Black liquor” <sup>3</sup>	G	F
Bleach liquor <sup>3</sup>	G	F
Borax	G	IL
Boric acid	G	IL
Brine (calcium or sodium chloride)	G	G
Calcium bisulfite <sup>10</sup>	G	F
Calcium chloride	G	G
Calcium hypochlorite <sup>3</sup>	G	F
Cane sugar liquors	G	IL
Carbolic acid (phenol)	P	P

TABLE 21-2. CHEMICAL RESISTANCE OF LINING MATERIALS (Continued)

	Rubber	Plasticized Polyvinyl Chloride
Carbon disulfide	P	P
Carbon tetrachloride	P	P
Carbonic acid	G	G
Castor oil	G	IL
Caustic soda <sup>4</sup>	G	F
Caustic potash <sup>4</sup>	G	F
Chlorine, dry	P	P
wet <sup>3</sup>	G	F
water <sup>3</sup>	G	F
Chlorinated salt brine <sup>3</sup>	G	F
Chlorinated acid	F	P
Chlorox	G	G
Chromic acid <sup>5</sup>	P	F
Chrome-plating solution	P	G
Citric acid	G	IL
Coconut oil <sup>2,10</sup>	G	F
Copper chloride	G	G
Copper sulfate	G	G
Copper cyanide (in solution with alkali cyanides)	G	G
Cottonseed oil <sup>3</sup>	G	F
Creosote, crude <sup>10</sup>	P	P
Developing solutions	G	G
Epsom salts	G	G
Ethylene glycol	G	IL
Fatty acids	F	IL
Ferric chloride	G	IL
Ferric sulfate	G	G
Ferrous sulfate	G	G
Fluoboric acid	G	G
Fluosilicic acid	G	G
Formaldehyde, 40%	G	IL
Formic acid <sup>6</sup>	G	F
Fruit juices <sup>1</sup>	G	IL
Fumaric acid	G	IL
Gallic acid	G	IL
Glauber's salt	G	G
Glucose	G	G
Glue	G	IL
Glycerine; glycerol	G	IL
Hydrobromic acid	G	IL
Hydrochloric acid <sup>7</sup>	G	F
Hydrocyanic acid	G	IL
Hydrofluoric acid <sup>8</sup>	F	F
Hydrofluosilicic acid	G	IL
Hydrogen peroxide <sup>9</sup>	G	G
Hydrogen sulfide, wet	G	IL
Hydroquinone	G	IL
Hypochlorous acid <sup>3</sup>	G	F
Hypo solution	G	G
Lactic acid <sup>1</sup>	G	IL
Lead acetate	G	IL
Lead nitrate	G	IL

TABLE 21-2. CHEMICAL RESISTANCE OF LINING MATERIALS (*Continued*)

	Rubber	Plasticized Polyvinyl Chloride
Lime bleach <sup>8</sup>	G	F
Lime water	G	G
Lye solution <sup>4</sup>	G	F
Magnesium chloride	G	G
Magnesium hydroxide	G	GL
Magnesium sulfate	G	G
Mallic acid	G	HL
Maleic acid	G	HL
Maleic anhydride	G	HL
Mercuric chloride	G	HL
Mine water, acid	G	G
alkaline	G	G
Mineral oil <sup>8,10</sup>	G	F
Muriatic acid (hydrochloric acid) <sup>7</sup>	G	F
Mustard	G	HL
Nickel acetate	G	G
Nickel chloride	G	G
Nickel nitrate	G	G
Nickel sulfate	G	G
Nitric acid <sup>11</sup>		
15° Baumé, maximum <sup>10</sup>	G	G
35% maximum (25.6° Bé)	P	G
Nitro cake	G	G
Oleic acid	F	HL
Oxalic acid	G	HL
Palmitic acid	F	HL
Phosphoric acid <sup>12</sup>	G	G
Plating solutions:		
Brass	G	G
Cadmium	G	G
Copper, cyanide	G	G
Copper, acid	G	G
Gold	G	G
Indium	G	G
Chrome <sup>13</sup>	F	G
Lead	G	G
Nickel, gray	G	G
bright	G	G
Rhodium	G	G
Silver	G	G
Tin	G	G
Zinc	G	G
Potassium antimonate	G	G
Potassium bisulfite <sup>10</sup>	G	F
Potassium acid sulfate	G	G
Potassium cuprocyanide	G	G
Potassium chloride	G	G
Potassium cyanide	G	F
Potassium hypochlorite <sup>8</sup>	G	F
Potassium carbonate	G	G
Potassium chlorate	G	G
Potassium phosphate	G	G
Potassium sodium tartrate	G	HL
Potassium sulfate	G	G
Potassium thiosulfate	G	G

TABLE 21-2. CHEMICAL RESISTANCE OF LINING MATERIALS (*Continued*)

	Rubber	Plasticized Polyvinyl Chloride
Potassium sulfite	G	G
Pyroligneous acid	G	IL
Sal ammoniac	G	G
Salicylic acid	G	IL
Salt brine	G	G
Sea water	G	G
Soda ash (sodium carbonate)	G	G
Sodium salts (see potassium salts)	G	G
Sodium hydroxide <sup>4</sup>	G	F
Sodium phosphate, tri	G	G
Sodium perborate	G	IL
Stannous chloride	G	G
Stannic chloride	G	G
Sugar solutions	G	IL
Sulfite liquors <sup>3</sup>	G	F
Sulfur dioxide water <sup>3</sup>	G	F
Sulfurous acid <sup>3</sup>	G	F
Sulfuric acid, 42° Bé maximum	G	G
Tannic acid	G	IL
Tartaric acid	G	IL
Triethanolamine	G	IL
Vinegar <sup>1,3</sup>	G	F
Vegetable oils <sup>3</sup>	G	F
Water	G	G
White liquor <sup>3</sup>	G	F
Whiskey and wines <sup>1</sup>	G	G
Zinc acetate	G	G
Zinc chloride	G	G
Zinc sulfate	G	G
Zeolites	G	G

<sup>1</sup> Discoloration and contamination is often a factor.

<sup>2</sup> Plasticized polyvinyl chloride is classed as F since some effect on plasticizer results especially at temperatures above 90°F. Applies to all alcohols mentioned.

<sup>3</sup> Very slight effect on plasticized polyvinyl chloride up to 90°F.

<sup>4</sup> Very slight effect on plasticized polyvinyl chloride by 35% at 90°F and by 10% at 150°F.

<sup>5</sup> Very slight effect on plasticized polyvinyl chloride by 35% up to 130°F.

<sup>6</sup> Plasticized polyvinyl chloride shows little effect up to 90°F with 90% acid.

<sup>7</sup> Very slight effect on plasticized polyvinyl chloride up to 90°F with concentrated acid, 22% acid has little effect up to 140°F on plasticized polyvinyl chloride. Discoloration is often a factor. By-product acid with small amounts of organic impurities should be carefully checked.

<sup>8</sup> Refers to 60% maximum concentration—only slight effect on plasticized polyvinyl chloride at 90°F. Soft rubber recommended up to 50% at 90°F.

<sup>9</sup> Refers to 3% maximum at room temperature. Plasticized polyvinyl chloride has been found satisfactory for use with 30% hydrogen peroxide. Most other linings cause decomposition of 30% concentration.

<sup>10</sup> Applies to 70°F maximum.

<sup>11</sup> Very little effect on plasticized polyvinyl chloride with 35% at 90°F, with 20% at 120°F, and with 10% at 150°F.

<sup>12</sup> Refers to 85% maximum. Contamination and discoloration are usually important.

<sup>13</sup> Will handle most chrome-plating baths up to 25% chromic acid, 130°F maximum.

crude rubber as 1, can be summarized: GR-S—0.8, nitril—1.0, butyl—0.6, neoprene—0.8, Thiokol FA—0.4. Under compression, soft rubber will distort. True hard rubber can be subjected to 10,000 to 15,000 psi at room temperature before distorting markedly.

**Corrosion Resistance.** Resistance to acids, alkalis, and other chemicals is important in a rubber compound that is to be used for lining tanks, making hose, lining pipe, and for similar services where chemicals are contacted. Temperature is an important factor in the chemical resistance of rubber. Diffusion, absorption, and oxidation are greatly accelerated by increases in temperature. Hard rubber exhibits better corrosion resistance than soft, but it has some drawbacks, such as brittleness, in many applications. Crude-rubber compounds have been used most widely as lining materials, but such American rubbers as butyl, nitril, neoprene, and GR-S have been applied very successfully in many cases where crude would not be satisfactory.

Table 21-2 indicates the resistance of crude-rubber compounds to various chemicals. It refers principally to the applications of rubber to chemical-process equipment.

**Abrasion Resistance.** Pure-gum compounds, consisting of rubber and sulfur, may exhibit high resistance to the abrasive action of small particles traveling at considerable velocities, as in a sandblast. However, most abrasion of a grinding nature is resisted better by compounds containing carbon black (made by burning natural gas with restricted oxygen supply), zinc oxide, or other reinforcement. Increased resistance to cutting and tearing generally accompanies increased abrasion resistance. Moisture absorption by a rubber compound reduces its abrasion resistance, but an abundance of water acts as a lubricant. Table 21-3 shows properties of typical abrasion-resisting compounds.

TABLE 21-3. PROPERTIES OF TYPICAL ABRASION-RESISTING COMPOUNDS

Compound	Typical Use	Tensile Strength, psi Cross Section	Elongation, %	Hardness Shore Durometer Type A	Specific Gravity
Armorite A	Chute lining	4000	600	55	1.13
Armorite B	Impact	4000	600	65	1.15
Armorite C	Sand-blast tube	3500	850	40	.93
Shoe heel	....	2000	400	70	1.40
Shoe sole	....	2100	380	90	1.26
Floor mat	....	400	200	80	1.48
Tiling	....	600	20	95	2.00



TABLE 21-4. PROPERTY RELATION OF AMERICAN AND CRUDE RUBBER

Property	Comparison to Rubber					
	Crude (Natural) Rubber	Neoprene GR-M ‡	Thiokol	Ameripol D (Nitril Type)	Ameripol F (GR-S Type) §	Butyl GR-I
Workability	Excellent	Good	Fair	Good	Good	Good
All American rubbers can be worked on rubber machinery, but in some products they are more difficult and expensive to fabricate than crude rubber owing to lack of tack.						
Vulcanising properties	Excellent	Excellent	Fair	Excellent	Excellent	Good
Adhesion to metals	Excellent	Excellent	Poor	Excellent	Excellent	Good
Adhesion to fabrics	Excellent	Excellent	Fair	Good	Good	Good
Resistance to swelling in lubricating oil	Poor	Good	Excellent	Excellent	Poor	Poor
Resistance to deterioration in oil	Poor	Excellent	Fair	Excellent	Poor	Good
Resistance to aromatic hydrocarbons (benzol, toluene, xylene, etc.)	Poor	Poor	Good	Fair	Poor	Fair
Resistance to chlorinated hydrocarbons	Poor	Poor	Good	Good	Poor	Poor
Resistance to lacquer solvents	Poor	Poor	Good	Fair	Poor	Poor
Gas diffusion	Fair	Good	Excellent	Good	Fair	Excellent
Resistance to diffusion of petroleum products	Poor	Fair	Excellent	Excellent	Poor	Poor
Adaptability for contact with food *	Excellent	Fair	Poor	Fair	Fair	Good
Dielectric strength *	Excellent	Fair	Fair	Fair	Excellent	.....
Electrical conductivity *	Fair	Fair †	Fair	Fair †	Fair	Fair
Resistance to water absorption *	Fair	Good	Fair	Good	Good	Fair
Resistance to strong oxidizing agents	Poor	Poor	Poor	Poor	Poor	Good
Resistance to other corrosives	Good	Good	Good	Good	Good	Good
Tensile strength *	Excellent	Good	Fair	Excellent	Good	Fair
Elongation	Excellent	Excellent	Fair	Excellent	Good	Excellent
Resistance to cold flow *	Excellent	Good	Poor	Excellent	Excellent	Fair
Resistance to sunlight *	Fair	Excellent	Excellent	Good	Fair	Excellent
Resistance to ozone *	Fair	Excellent	Excellent	Good	Fair	Excellent
Resistance to aging	Good	Excellent	Excellent	Excellent	Excellent	Excellent
Approx. specific gravity basic material	.93	1.23	1.34	1.00	.94	.92
Heat resistance *	Good	Excellent	Poor	Excellent	Excellent	Excellent
Flame resistance	Poor	Good	Poor	Poor	Poor	Poor
Cold resistance *	Excellent	Good	Fair	Good	Excellent	Good
Rebound elasticity (snap)	Excellent	Good	Good	Fair	Good	Poor
Abrasion *	Excellent	Good	Poor	Excellent	Excellent	Fair
Tear resistance *	Excellent	Good	Poor	Good	Fair	Good
Abrasion resistance—soaked in oil	Poor	Fair	Poor	Excellent	Poor	Poor
Hardness Durometer A tests (100 is bone-hard)	20 to 100	20 to 90	35 to 80	20 to 100	35 to 100	15 to 90
Color range	Good	Good	Poor	Good	Good	Good
Freedom from odor *	Excellent	Fair	Poor	Fair	Good	Good
Resistance to paint and ink driers	Poor	Excellent	Excellent	Excellent	Excellent	Excellent

\* These properties available only in specific compounds.

† Electrically-conductive compounds having more "rubbery" characteristics can be made of these American rubbers than with crude rubber which has to be very heavily "loaded" to attain the same degree of conductivity.

‡ GR-M is an abbreviation for "Government Rubber—Monovinylacetylene."

§ GR-S is an abbreviation for "Government Rubber—Styrene."

|| GR-I is an abbreviation for "Government Rubber—Isobutylene."

## SPECIFIC PROPERTIES FROM COMPOUNDING

Today rubber manufacturers have three main ways in which they can build into a compound various properties they may desire:

1. They have at their disposal natural rubber and a wide assortment of man-made elastomers.

2. They may choose from a wide variety of compounding materials other than rubber and rubber-like substances—fillers, plasticizers, anti-oxidants and the like.

3. They may regulate the quantities of the various materials that are mixed to form a compound. Because of the almost endless assortment of available properties a rubber or rubber-like compound can be given, the rubber manufacturer has to be supplied with full information about the end use of a product before he can be expected to produce a material that will satisfactorily fulfill its mission:

A comparison of the properties which can be obtained from some synthetic elastomers with those of crude-rubber compounds is given in Table 21-4.

## RUBBER BELTING

Most rubber belting is laminated. Its structure consists of various layers or plies of textile fabric or cords in combination with layers of rubber, all united into a single structure during the process of vulcanization. Sometimes, to obtain certain advantages, cords or grommets of steel or other special materials are included in the belt structure, as in a steel-cord conveyor belt.

## RUBBER V BELTS

A V belt (Fig. 21-3) is a flexible power-transmitting unit whose cross-sectional shape usually resembles the letter V with some of the bottom cut off. The wider portion is the top, the narrower truncated surface is the bottom, and the sloping surfaces the sides. V belts are commonly made by combining layers of fabric and rubber, with perhaps reinforcing grommets of cotton, rayon, steel, or other high-strength material extending around the central portion. Rubber V belts are commonly classified as fractional horsepower or fhp, multiple, automotive, agricultural, railroad, and open end. Metal-fastening devices are necessary to join open-end V belts, which are used on machine tools and other equipment that would have to be dismantled to permit installation of a conventional V belt. A recent development is the

static-control V belt made of rubber capable of conducting electricity and used where accumulations of static charges might be a hazard.

A rubber V belt running in a grooved sheave grips the sides of the groove—it should not touch the groove bottom. The gripping action develops as the belt bends around the sheave, because compression of

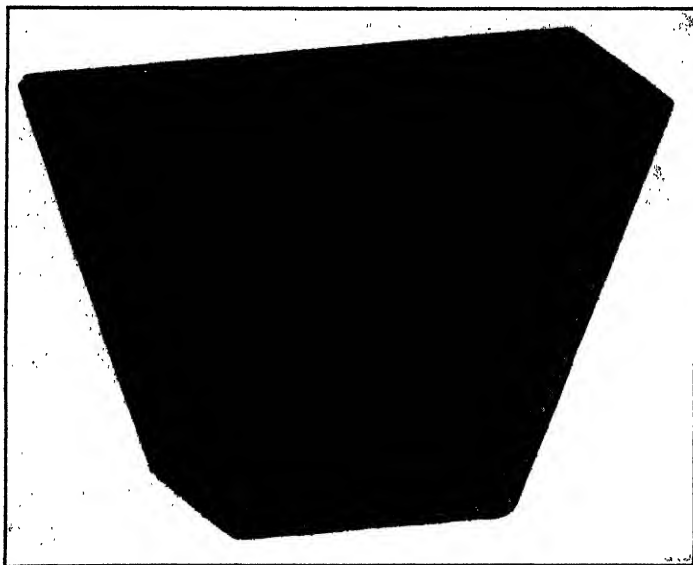


FIG. 21-3. Cross Section of One Type of V-Belt Showing Relationship of Cords and Rubber.

the belt structure causes an outward expansion. As the belt straightens on leaving the groove, the grip is released without drag.

#### FLAT RUBBER BELTING

In this group of rubber laminates (Fig. 21-4) are such products as power-transmission belting, conveyor belting, and elevator belting. The usual construction includes plies comprised of cotton fabric or cord bonded together by a soft-rubber compound. The textile layers provide most of the tensile strength and carry most of the load. The function of the rubber is to unite the textile elements, protect them from moisture, shield them from abrasion and shock, reduce friction between them, and provide a belt surface that is resilient and that grips pulleys satisfactorily.

## POWER-TRANSMISSION BELTING

Two main types are fabric and cord belts. The first is produced by vulcanizing together plies of rubber-impregnated cotton duck, often with thin layers (skim coats) of rubber between, and sometimes with thicker rubber surface layers. The cord type consists of individual lengthwise textile cords sandwiched between woven duck plies, the whole welded into a unit by vulcanized rubber. Cords may comprise one layer or may be in more than one ply with rubber between. Cotton duck used in belts is often classified according to its weight, but this is not a dependable index of its efficiency as an element of a belt.

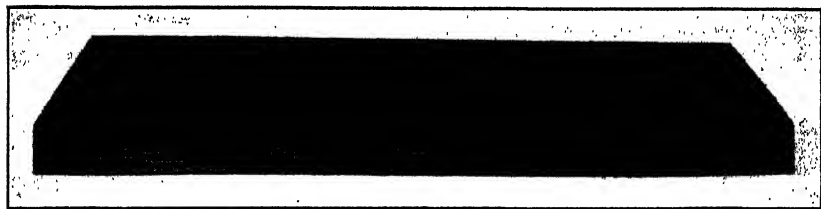


FIG. 21-4. Ply Arrangement in Flat Rubber Conveyor Belt.

Batches of duck having the same yarn size and other characteristics will exhibit different properties of stretching and power-transmitting ability when built into a belt.

In the installation and operation of a flat belt, it is desirable not to stretch the belt to its limit. The belt absorbs shock best when there is a slight degree of elastic stretch. (In elastic stretch the elastic limit is not reached, and the belt resumes its original length when tension is removed.)

The tensile strength of a rubber belt is not an index of its ability to transmit power. A belt whose ends are joined by a vulcanized splice can transmit about 15 per cent more power than one joined by metal fasteners; yet, its tensile strength is about twice that of the metal-fastened belt.

Relations between flat rubber transmission belts and their pulleys are important. Pulley diameters should not be too small, as Table 21-5 indicates.

By keeping pulley diameters relatively large, high belt speeds are achieved, contact between belt and pulley is better, and slipping is reduced, extreme flexing that causes ply separation is avoided, and belt cross sections can be kept at a minimum. Between 4000 and 4500

TABLE 21-5. MINIMUM PULLEY DIAMETERS, INCHES

Thickness	1000 fpm	3000 fpm	6000 fpm
Highflex			
3-ply	3	4	5
4-ply	5	6	8
5-ply	7	8	12
6-ply	10	12	16
7-ply	13	16	20
8-ply	16	20	24
9-ply	19	24	28
10-ply	22	28	32
Highflex, Jr.			
Light single	2	3	4
Medium single	3	4	5
Heavy single	4	5	7
Light double	6	7	10
Medium double	9	11	15
Heavy double	11	13	17
Multicord			
Widths up to 8 in.			
Extra light	3	3	4
Light	4	5	7
Medium	6	7	10
Heavy	8	10	13
Widths 8 in. and over			
Extra light	5	7	10
Light	8	10	13
Medium	10	13	16
Heavy	13	16	19
Extra heavy	16	19	23

fpm seems to be the range of preferable speeds. The relation between diameters and speeds in rpm of driving and driven pulleys can be calculated by use of the formula,

$$DR = dr$$

where  $D$  = driving-pulley diameter

$R$  = driving-pulley rpm

$d$  = driven-pulley diameter

$r$  = driven-pulley rpm

**Horsepower Capacity.** It is assumed that heavy fabric belting exerts a  $13\frac{3}{4}$ -lb pull for each ply per inch of width. Thus, 1 hp will

be transmitted per ply inch at a belt speed of 2400 fpm. At half the speed, half the horsepower would be transmitted. Horsepower can be calculated by use of the formula,

$$\text{hp} = \frac{WPS}{2400}$$

where  $W$  = width of belt in inches

$P$  = ply number

$S$  = speed belt travels in fpm

The horsepower thus calculated may not be the exact horsepower of the drive because of such influencing factors as arc-of-contact correction, pulley-surface correction, and centrifugal-force correction. The coefficient of friction between a rubber-surfaced belt and a steel pulley usually ranges from 0.22 to 0.30. The coefficient increases with belt speed; and horsepower can also be increased as much as 35 per cent by applying a special surface to the belt. Use of a pulley facing of wood, paper, or fiber may boost horsepower capacity as much as 10 per cent. At a belt speed no higher than 4000 fpm, and for some improved belts under considerable initial tension up to 6000 fpm, effects of centrifugal force on horsepower transmitted may be ignored.

**Belt Slippage and Bearing Loading.** In a flat-belt drive operating at rated horsepower and having a  $180^\circ$  arc of contact, the tension per inch of width per ply is not over 35 lb. Pulley-bearing pressure equals the total of tensions in both belt strands, and this pressure load is proportioned between the two adjacent pulley or shaft bearings, the nearer one enduring the greater burden. To find the total bearing load in pounds (for a  $180^\circ$  wrap of belt around pulley) the belt width in inches is multiplied by the number of fabric plies and then multiplied by 35. There are several causes of belt slippage. One of these is too much slack in the part of the belt moving from driving to driven pulley, which reduces the force holding the belt against the pulley. Increasing belt tension helps remedy this at speeds up to about 4000 fpm. At greater speeds, centrifugal force cancels the effects of increased tension. Another cause of belt slipping is insufficient area of contact with the pulley. The shorter the arc of contact, the greater the tendency to slip. Standard belt calculations and tables are based on a  $180^\circ$  arc. A third cause of slipping is a low belt-to-pulley frictional coefficient. Factors tending to reduce slippage include smoothness, dryness, and cleanliness of belt and pulley surfaces, and pliability and softness of belt.

It is impossible to eliminate belt slipping entirely, for there is a normal creep that accounts for a driven-pulley speed loss of 1 to 1½ per cent. This creep develops because, in curving around a pulley, the belt actually experiences a change in length. That is, a section which is 1 in. long traveling in a straight line on the tight side of the belt is somewhat shorter (say 0.99 in.) when traveling on the slack side.

### CONVEYOR BELTS

Rubber conveyor belts are moving highways used for transporting speedily and economically, along level routes or up moderate inclines, such materials as crushed rock, dirt, sand, gravel, slag, ore, coal, machinery parts, manufactured goods, packages, ice, and food products. When a belt operates at a steep or vertical angle and is equipped with buckets or similar devices, it becomes an elevator belt for handling similar materials. A typical conveyor belt construction consists of cotton duck plies alternated with thin rubber plies, the assembly wrapped in a rubber cover, and all elements united into a single structure by vulcanization. Plies may be folded like flat tubes, a single seam occurring for every two plies in 26-in. belts and smaller. When plies are simply stacked without folding, widths up to 72 in. can be made without lengthwise seams.

When a conveyor belt must withstand heavy impacts and other abuse, it may be made with textile or metal cords replacing some of the woven fabric reinforcements. A typical textile-cord conveyor-belt reinforcement may consist of two woven duck plies, a layer of longitudinal cords, and a layer of transverse cords. All the plies are united by thin layers of rubber, and the belt has an outer rubber cover designed to withstand severe wear. Such a belt is more flexible, assumes a trough shape easier, and stretches less than a similar all-fabric belt. Additional plies may be built into the middle portions of some conveyor belts that are to withstand extra abuse in handling ore, slag, and the like; or the plies may remain uniform, and the cover be made thicker along the middle. Temperatures up to 150°F will not damage ordinary conveyor belts seriously, although a maximum of 125° is usually recommended. For handling hot slag and other hot materials, covers made of special American-rubber compound are used. The precise temperature the belt will withstand depends somewhat on atmospheric temperature and the fineness of the material carried, but the maximum usually recommended is 225° to 250°F. In some cases, heat damage can be lessened by the use of devices that hasten load

cooling by stirring. A limiting factor in hot-belt design is the 300°F charring temperature of cotton fabric.

Surface coverings of conveyor belts are matched to the service. Normally, a smooth rubber surface is used, the compound being designed to resist oil when required; but a textured surface may be employed—such as an exposed duck cover for bakery products, a duck-impression rubber surface for sliced fruit, and a variety of roughened surfaces for carrying ice blocks, luggage, and the like.

Conveyor belts of woven fabric construction are classified according to the number of plies, each ply averaging  $\frac{1}{16}$  in. in thickness, and cord-belt thickness is often given in terms of the number of heavy fabric belt plies it equals. In designing conveyors, the number of belting plies needed to withstand the maximum expected tension is calculated by determining the working tension of the belt in terms of pounds per inch of belt width, that is, by dividing the total running tension of the belt by the belt width in inches.

Cord conveyor belts are considered superior to fabric belts, because they resist tearing, gouging, and cutting actions better, resist blistering when subjected to acid, assume trough shape more readily, and withstand impact better at speeds greater than 500 fpm when handling large lumps or when idlers are about 4 ft apart. Cord belts, being softer, are expected to stand up better under excessive abrasion. Stress applied to a cord belt is not multiplied in the plies as it is in a fabric belt. Because warp threads in a fabric bend back and forth over filler threads, tension applied in the direction of the warp tends to straighten the bends. This causes an actual increase of tension in the warp, the increase for a 45° bend being as great as 40 per cent in 42-oz duck.

#### ELEVATOR BELTS

By attaching buckets or other carrying devices at intervals along the outer surface of a flat belt, an elevator belt is produced and is useful for moving materials from one level to another. A scoop-feed or spaced-bucket elevator has considerable separation between the buckets, which are loaded by scooping into the grain or other material and are discharged by centrifugal force. A continuous-bucket elevator has closely spaced buckets and moves at a speed slow enough to permit buckets to empty themselves by pouring. It will operate at flat angles.

Elevator belts must be stronger than conveyor belts of the same width, and, therefore, are built with more plies. Thickness of the rubber cover is usually increased to offset rapid pulley-side wear. In



spite of the ruggedness of an elevator belt, it can be damaged by material caught between it and the lower (boot) pulley. Care in feeding material to the belt, and use of a squirrel-cage boot pulley help reduce such trouble.

An elevator belt is subjected to greatest tension where it is starting to bend over the top (head) pulley. This tension is a summation of the following: one-half total weight of belting, one-half total weight of empty buckets, bearing and boot friction, greatest total weight of material being carried in buckets, and the initial belt tension.

### RUBBER-LINED EQUIPMENT

Rubber, in one or more layers, is employed to protect metal pipes, tanks, and other equipment used in handling various corrosive liquids. Usually the rubber is applied as a lining for a steel tank or pipe that is to hold or carry acids. Pickling tanks employed in the steel industry are examples. Among other industrial equipment in which rubber is used as a lining are chemical storage tanks; railway tank cars used for transporting acids, food products, and the like; electroplating tanks; steel drums and barrels; chemical-carrying pipes and valves for controlling flow; and stacks for carrying plating-plant fumes.

**Lining Materials.** These include:

(a) Crude-rubber compounds—considered preferable for most industrial services such as the handling of hydrochloric acid—applied in the form of soft-, semihard-, or hard-rubber compounds.

(b) Butyl rubber, used as a soft compound.

(c) Nitril, used as soft-, semihard-, or hard-rubber compound.

(d) Neoprene, applied as a soft-rubber compound, and used where resistance to oils and hydrofluoric acid is desirable.

(e) GR-S, in the same degrees of hardness as crude rubber.

(f) Vinyl elastomers, such as plasticized polyvinyl chloride, of which Koroseal flexible synthetic is an example. Koroseal linings are useful, particularly where nitric acid and oils must be withstood.

(g) Latex rubber, which may be made from crude or one of the American rubbers. The compound is deposited from a latex solution, directly on the metal surface to be covered. The deposited layer is subsequently vulcanized. The latex may form a lining for a vessel, or may cover both inside and outside surfaces of such articles as perforated baskets used in handling parts in electroplating solutions. Most metals except magnesium can be covered by the anode process of depositing electrically charged particles of latex compound. Properties

of a latex covering are approximately the same as those of milled-rubber compounds. Tensile strength is somewhat greater, but abrasion resistance is lower than for corresponding milled-rubber compounds.

**Attaching the Lining.** The Vulcalock process of bonding rubber to steel (see section on rolls) is used in applying milled-rubber linings to chemical tanks and the like. The lining is first applied to the metal by hand, much as a room is papered. Extra thicknesses may be added over rivets and other structural points, or where the lining might be subjected to extra abuse. The lining is then vulcanized as a unit, to develop the desired properties in the lining compound and to develop

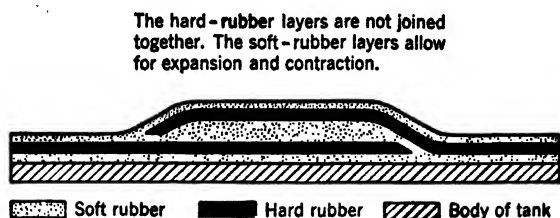


FIG. 21-5. Triflex Expansion Joint.

the adhesive bond between lining and metal. Linings of containers too big to be placed in vulcanizers are cured by admission of steam. The vulcanized lining does not add to the structural strength of the tank, its purpose being to prevent chemicals from attacking the tank, prevent contained fluids from being contaminated by the tank material or other substance, and to protect the tank from abrasion.

**Lined Materials.** Rubber linings can be bonded to ordinary steel, stainless steel, brass, aluminum, concrete, and wood. Often the use of a lining with ordinary steel eliminates the necessity of using a stainless alloy. Adhesion to aluminum is inferior to that to steel. Covering for brass must be compounded according to the composition of the metal.

**Combination Linings.** A true hard rubber resists acids and many other chemicals better than softer compounds. However, the use of hard rubber alone as a tank lining leads to difficulties because of its brittleness. A way of overcoming this without losing the desirable hard-rubber properties consists of laminating hard and soft compounds. In one type, Fig. 21-5, a layer of hard rubber is sandwiched between two layers of soft rubber, and this sandwich (which is usually about  $\frac{3}{16}$  in. thick) is bonded to the tank wall. Provisions must be made for expansion and contraction of the lining, and the joint must be made in such a way that adjacent hard-rubber layers do not come into con-

tact with each other but are separated by soft rubber that permits some movement.

The soft rubber in Triflex lining provides the desired resistance to abrasion, shock, and temperature variation, while the hard rubber contributes a superior chemical resistance.

**Lining Thickness.** Most tank linings are about  $\frac{3}{16}$  in. thick. For light-duty service,  $\frac{1}{8}$  in. may be adequate; whereas for heavy pickling tanks and similar equipment, the lining may be  $\frac{1}{4}$  in. or—in extremes— $\frac{3}{8}$  in. thick. Lining in steel pipe runs from  $\frac{1}{8}$  in. to  $\frac{1}{2}$  in.

Thickness and other characteristics of a lining usually depend on a number of factors such as service temperatures, chemical resistance desired, technical difficulties of installing the lining, and cost. Crude-rubber linings are serviceable to 200°F. This range can be increased to about 235° by applying over the lining a sheathing composed of one or two 4-in. layers of brick. A lining of soft crude rubber will withstand temperatures as low as -65°F.

Koroseal linings are used principally when there is no rubber compound that will do the job, as in the pickling of stainless steel with nitric-hydrofluoric acid solutions, and in chromium plating. Koroseal linings cannot be applied with a vulcanizing adhesive but require cements that set at normal temperatures. Therefore, they will not withstand so high an operating temperature as rubber. Because of the necessity of adding plasticizers, Koroseal linings do not have the same chemical resistance as do the harder forms of the synthetic. Such linings resist chromic acid, nitric acid, and other strong oxidizing agents; can be applied to a thickness of  $\frac{3}{16}$  in., are readily repaired; have high electrical resistivity; and exhibit high resistance to light, water, gas diffusion, and oxidation.

Muriatic acid is the principal chemical handled in rubber-lined equipment. No rubber is entirely unaffected by it, but soft crude-rubber compounds are affected in such a way that a tough hard film forms on the lining surface. This film thereafter acts as a barrier to the acid, discouraging further reaction with the rubber. Muriatic acid does not form the protective film on various soft American-rubber compounds. Harder compounds of both crude and American rubbers resist this acid well. Sulfuric acid as high as 50 per cent concentration can be handled in tanks lined with soft crude or GR-S. Rubber linings will handle all plating solutions except chromium, for which polyvinyl chloride is used.

Testing of rubber-lined surfaces or similar laminated structures in which one member is a good electric conductor may be done electrically

by using a special portable high-frequency applicator devised for the purpose. Whenever a pinhole or other defect is approached by the applicator, the normally dispersed bluish discharge is concentrated into a bright spark passing through the break to the metal beneath.

## RUBBER-COVERED ROLLS

In order to produce a surface that is resilient and resistant to acids, that has superior frictional gripping properties, or that possesses some other advantage, rubber is used as a covering for various kinds of rolls, rollers, and pulleys.

Rubber-covered rolls are used extensively in the manufacture of paper. Among the largest of these are the press rolls used to squeeze water from the pulp sheet. These rolls have heavy cast-iron cores. It used to be universal practice to groove the core by taking a rough threading cut on a lathe, vulcanize over it a hard-rubber layer to serve as a base for the cover and to minimize blistering of the cover, and then vulcanize the soft-rubber cover to the hard rubber. Whenever a roll became worn and required re-covering, the rubber was stripped away and the iron core regrooved—this operation reducing the diameter of the core a little each time. The introduction of steel-jacketed press rolls has changed all this.

The steel-jacketed roll was made possible by the Vulcalock process of bonding rubber to steel, the bond having a tensile strength of 500 psi or more. It cannot be used for bonding rubber directly to a cast-iron core because the porosity and pitting of the iron prevent a uniform bond. So the cast-iron core is covered with a steel jacket, and the soft-rubber cover is bonded directly to the steel. When the cover becomes worn, it is simply stripped off, the steel surface cleaned by sandblasting, and a new cover vulcanized to the metal. No reduction in core diameter results.

Rubber also can be attached directly to such other metals as aluminum and brass, to form rolls used for various purposes. The gripping action between a flat belt and a pulley can be improved by lagging the pulley with a layer of soft rubber. This lagging may be secured with an adhesive and properly installed bolts, or it can be vulcanized directly to the pulley surface with the aid of Vulcalock cement. Molded-rubber rollers, wheels, casters, and similar products can be secured directly to brass hubs, cores, or other parts during the curing period, the brass elements being handled as inserts in the mold used to form the rubber.

Examples of rubber-covered rolls and similar articles include: paper-mill press rolls, used to squeeze water from pulp; paper-mill table, wire, and breast rolls; rolls used in factories to handle steel sheet in tin-plating machines and galvanizing equipment; rolls in pickling processes for holding the sheet under the acid bath, carrying it through the bath, and for wringing excess pickling solution from the sheet surfaces; textile rolls, used in the handling of wool, cotton, silk, and various synthetic textile products during such operations as dyeing, starching, and bleaching; rolls used in tanneries in connection with such operations as removing hair and flesh from hides, buffing, and splitting; typewriter platens and washing-machine wringer rolls; and ink rollers in printing presses.

#### OTHER RUBBER COVERINGS

Layers of rubber, often combined with fabric (Fig. 21-6) and other materials, are used widely in industry as a protection against such

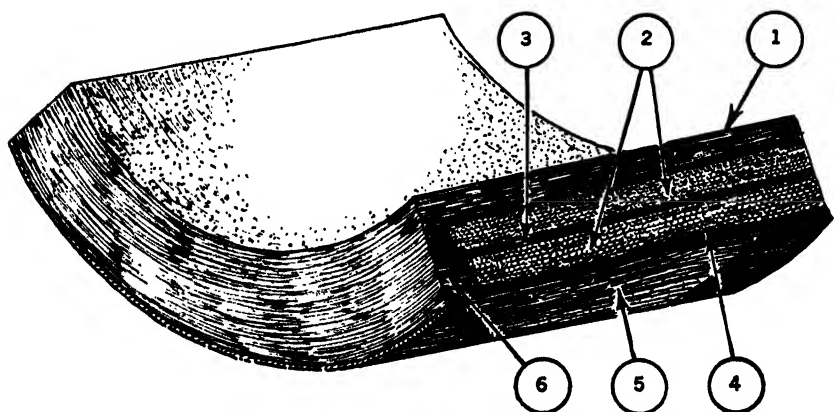


FIG. 21-6. Section of Armorite Dredging Sleeve Showing Construction:

1. Heavy Armorite tube.
2. Plies of heaviest fabric.
3. Layer of rubber interposed between the two middle plies to give added flexibility without any decrease in sturdiness.
4. Tough protective cover.
5. Clamp strip.
6. End sealed and heavily capped with rubber.

wear-producing actions as abrasion and shock. Armorite is a typical material and is used for such purposes as lining coal and ore chutes

and hoppers, protecting the blades of mixers handling abrasive materials, shielding fan blades and housings, lining sandblast cabinets, covering inside surfaces of pumps handling mud and other abrasive fluids, and forming protective cushions on which castings and other heavy objects are dropped.

Armorite, made in several forms, has a soft-rubber surface compounded specially to resist abrasion. Its tensile strength is about 4000 psi. The all-rubber type is used where maximum resistance to abrasion is desired. The fabric-fiber-base Armorite, incorporating two heavy duck plies between which is a layer of tough fiber, can be fastened down with bolts, nails, or screws. The material is made also without the fiber ply. Cements and mastic tar may be used for attaching any of the foregoing types to surfaces. There is also a steel-base Armorite in which the rubber is bonded to the base by the Vulcalock process.

Armorite is not oil-resistant, will withstand up to 150°F, and will endure any impacts the rubber thickness will absorb. It can be applied to irregular surfaces in the unvulcanized form, the covering then being cured as a unit. Edges of Armorite containing fabric are sealed, where exposed, by painting them with an edge-sealing rubber cement.

## RUBBER HOSE

In structure, nearly all rubber hose is laminated and is composed of layers of rubber combined with such reinforcing materials as cotton duck, textile cords, and metal wire. Hose is an answer to the demand for a *flexible* carrier for liquids, gases, and finely divided dry materials.

Simplest in structure is the nonlaminated hose consisting of a tubular extrusion of compounded rubber or plastic. Of equal simplicity is the type made entirely of textile fabric and used for soaking lawns (because water oozes through it). All-fabric hose has been used for fire fighting.

The modern laminated rubber hose can be made with an almost infinite variety of structures, but the following is common and typical: a layer of rubber compound comprising the lining and known as the "tube"—because that is precisely what it is; next, an intermediate layer consisting of one or more plies of braided cord or cotton duck impregnated with rubber; finally, forming the outside wear-resisting cover, another layer of rubber compound. These various laminations are united, by vulcanization, into a homogenous whole. Variations include the use of coiled-, woven-, or braided-wire plies as reinforcements between tube and cover, and the use of coiled wire as an inside or out-

side reinforcement to resist crushing and to increase resistance to abrasion and other abuse.

Several methods of hose manufacture are in use, each giving rise to various claimed advantages and limitations. In one method, the air-inflated uncured hose tube is fed through a machine that wraps around it a spiral of woven fabric or that braids over it a reinforcing layer of textile cord or other material. Next a layer of rubber compound is applied over the fabric by extrusion and, after this, a temporary jacket of lead. The lead forms a mold, and the rubber is cured by steam, while hot water is forced through the hose: the lead is later stripped off. By this "long-length cure" method, hose to 500-ft lengths (limit of shipping capacity) is made at a relatively low cost. Its surface is pleasing in appearance, and the long lengths reduce coupling costs. Hose is made by this method up to 1½ in. inside diameter (2 in. outside diameter). Because of limitations with respect to tension of the braided cord and variations in braiding angles, this construction generally is not used for extremely high pressures. Inside diameters of long-length hose are not held to close limits.

The second type of hose is made in lengths up to approximately 50 ft by inserting a steel-tube mandrel into a length of hose tube, placing over the tube one or more plies of cotton fabric or other reinforcement, following this with a layer of rubber cover stock, and finally binding the hose temporarily with fabric. During vulcanization by steam, this fabric wrapping acts much like the outside of a mold; it is then stripped off, leaving the hose cover with a characteristic fabric texture. Mandrel-cured hose is smooth and uniform in diameter on the inside and can be made to handle high pressures, because braided reinforcement can be applied under considerable tension and with less variation in angle of the strands. The outside of such hose is not so smooth and uniform as that which can be produced by curing in a lead jacket. Mandrel-cured hose generally does not withstand kinking so well as machine-braided hose, but it is less susceptible to breaking near couplings.

A third type of hose construction consists of weaving a textile cover over the rubber tube. In this way, familiar cotton-covered fire hose is produced. Wire can be incorporated in the weaving to produce added strength and stiffness in hose to be used for handling building-insulating material, water, gasoline, oil, and so on, under pressure or suction. In terms of the weaver's art the warp strands are parallel to the hose tube; the filler strands encircle it spirally. By weaving two jacket plies so

that the filler cords spiral in opposite directions, twisting of the hose under pressure is lessened.

In the construction of hose for a specific service, the manufacturer has at his disposal a wide variety of materials and ways of combining them. He can make hose whose chief attribute is flexibility, ability to carry high pressures, resistance to oil, ability to carry food products without contaminating them, skeletal strength so great that a truck can be driven over it without doing appreciable damage—or hose that has some other outstanding characteristic or a combination of them. By examining a few standard hose types briefly, some of these attributes become apparent.

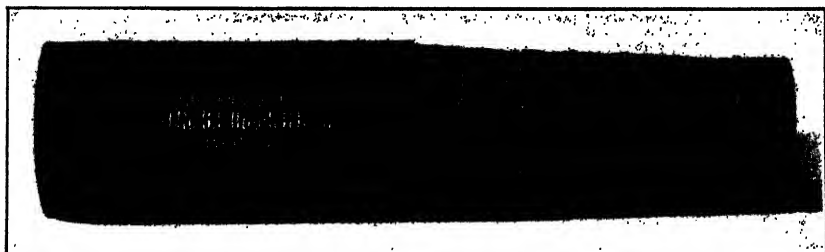


FIG. 21-7. Manifold Air Hose, Especially Developed for Transmitting Compressed Air from Pipe Line to Manifold.

Hose designed for handling acids, usually of mandrel-cured (wrapped-fabric) construction, is made of rubber compounds designed to withstand such chemicals as all acids except sulfuric, chromic, and nitric; nearly all alkalies, and most inorganic salts. Acid hose containing wire reinforcement is used in suction service, whereas soft hose intended for handling chemicals at the discharge end can be squeezed together by pinchcocks.

Air hose, one of the most widely used types, is designed to stand up under high internal pressures, to withstand rough handling without severe cover damage, to endure high temperatures (for example, 250°F), and to carry oil or oil vapor without disintegration of the tube. Air hose is made by the long-length braiding process involving layers of braided-cord reinforcement; by the mandrel-cured method, with as many as seven plies of woven cotton reinforcement; and by combining woven and braided plies in the reinforcing layer (Fig. 21-7).

Blowing hose is a light flexible type having a tube smoothness produced by mandrel curing and is used for handling, by suction or blowing, such materials as building insulation, dust, grain, and sawdust.



A type usually known as butane-propane hose is made of rubber that will withstand liquefied petroleum gases at pressures as high as 250 psi.

Cement-gun hose is used for blowing nozzle-mixed concrete into molds, and so on, and has a lining of abrasion-resistant rubber. Cement-handling hose, similarly lined and with spiral reinforcing wire, carries dry cement suspended in air traveling at high speed.

Sand and cement discharge hose carries mixed concrete and has an abrasion-resisting tube of extra thickness. Cement grout or mud hose is of the same type, but has more fabric plies because it must withstand pressures as high as 1000 psi in connection with tunnel and dam construction.

In rotary oil-well drilling, a hose of rugged construction and capable of withstanding the high pressures (for example, 1000 psi) involved in deep-well work, is used. Driller's hose manufactured by the B. F. Goodrich Co. has a patented reinforcement made by applying metallic mesh tape in crossed helical windings.

Hose designed for handling gasoline at pumps has a smooth tube made of American rubber that is compounded to withstand gasoline and oil. The cover is of similar compound and is designed also to resist sunlight and rough handling. To prevent trouble from static electric discharge, a flexible wire wound spirally is incorporated in this hose and is connected to fittings at both ends. There are special types of hose designed for handling fuel oil, gasoline, and crude petroleum at refineries and bulk stations and on barges and tankers. Some of this hose contains wire reinforcement to prevent crushing. The sea-loading type resists barnacle damage during long immersion in the ocean (Fig. 21-8).

Hydraulic-control hose is designed to resist some of the highest pressures that hose encounters. The reinforcement is of a high-strength construction such as two braided steel-wire layers with rubber between. Hose tube resists oil and grease. It is used on machine tools, pressure-greasing equipment, dump trucks, construction machinery, and other applications involving the handling of oil. It is used also for carrying gases under pressure.

Welding hose is used for oxygen, hydrogen, acetylene, and air. It is reinforced with cotton fabric or cord and is light and flexible. A red cover is used on hose intended for acetylene or hydrogen, whereas a black or green cover is used to indicate hose suitable for oxygen or air.

Sandblast hose has a tube compounded to resist abrasive action of sharp particles traveling at great velocity.

Steam hose must be built to endure high pressure at temperatures above 212°F. Textile fibers used in steam-hose reinforcement will withstand only a limited amount of heat before charring and must be protected by rubber of low heat conductivity. An all-wire reinforcement consists of steel-wire tape braided in such a way that hose expansion is sufficient only to permit couplings to be installed. A typical steam hose reinforced with fabric plies will carry saturated steam at 150 psi and superheated steam at 366°F.

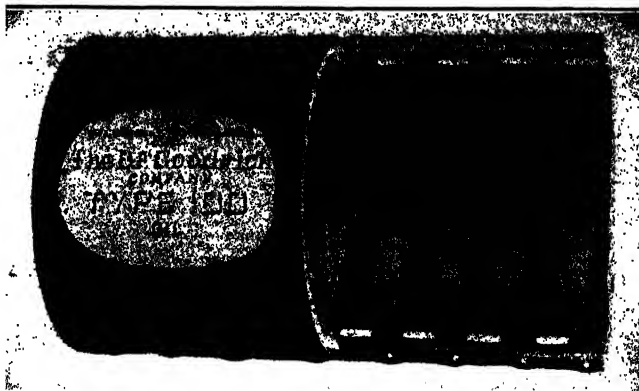


FIG. 21-8. Hose for Loading Oil into Barges, etc., at Docks.

Suction hose, such as that designed for the dredging of sand, is reinforced by steel wire wound in a spiral. This prevents crushing and keeps the hose walls from collapsing under suction. When the wire is part of the reinforcement intermediate between tube and cover, the hose has a smooth bore. When the wire spiral is placed inside the tube so that it is exposed to the flow, a rough-bore hose results. A typical smooth-bore suction hose has a tube  $\frac{1}{2}$  in. thick.

Spiralock hose, a type intended for excavating and similar applications, is reinforced by a steel-wire spiral, the coils of which are anchored in position by being encircled by part of the adjacent friction fabric (Fig. 21-9).

Vacuum hose is of fabric-ply construction with a steel-wire spiral to prevent collapse and is used for air suction. Nonsuction water hose, heavier than domestic garden hose, is intended for handling water under high pressures in industrial work.

**Hose Couplings.** Hose, to be useful, must be joined to pipes, valves, and so on, and to other hose sections. For this purpose, numerous

types of couplings—usually made of iron, brass, or aluminum—have been developed. Some couplings are joined or attached to pipes and the like by threads; others are designed for quick connection or release by bayonet or other “threadless” action. A coupling must be attached to a hose so securely that it will not blow out under any pressures the hose will withstand and in such a way that the hose adjacent to the coupling is not weakened. Clamps tightened by bolts, wire windings, coupling sleeves expanded by internal pressure, collars or ferrules



Fig. 21-9. Spirallock Hose with Smooth Bore.

crimped around hose cover, couplings having “teeth” that grip wire reinforcement—these are among the methods used for securing fittings to hose.

### VIBRATION INSULATORS

Laminated structures in which soft resilient rubber is placed between and vulcanized to metal pieces are used as flexible mountings for instruments, machinery, electrical devices, and other equipment. When vibration is produced in the machine itself, rubber mounts prevent the disturbing frequencies from traveling beyond the machine and thus protect adjacent equipment, buildings, and personnel. When vibration and shock come from an outside source, the mountings prevent the disturbance from reaching the instrument or machine.

Rubber is combined in various ways with metal to produce flexible mountings. In Vibro-Insulators, the rubber compound is attached to the metal by the Vulcalock process. Types of insulators include:

Flexible rubber section sandwiched between two flat areas of steel. The steel members are equipped with threaded studs, flat strips projecting at right angles, or other means of attaching to machine or to floor. The insulator is mounted so that the rubber-steel sandwich is

vertical, the rubber being stressed in shear (Fig. 21-10). A modification consists of two rubber strips between steel sidepieces and a central channel, the machine to be isolated being fastened to the channel or the sidepieces.

Another form consists of a rubber tube or cylinder vulcanized to two concentric vertical metal tubes, the rubber being deflected in shear.

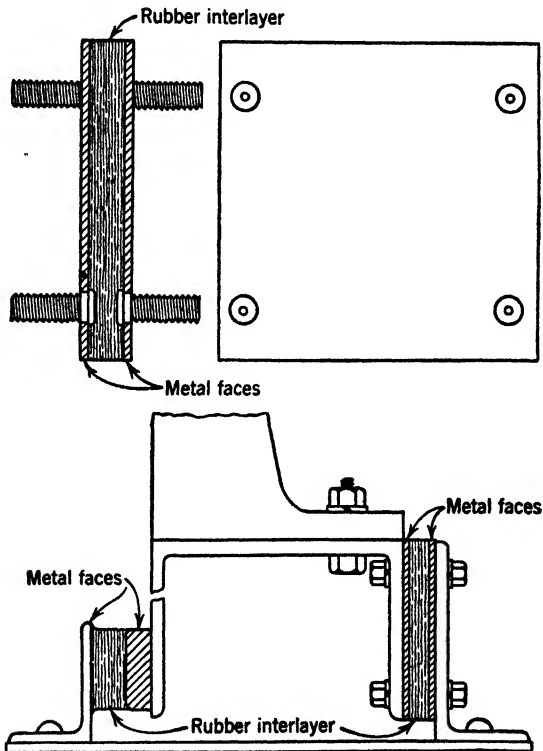


FIG. 21-10. Vibro-Insulators Consisting of Rubber Sandwiched between Flat Steel Surfaces, in Turn Attached to Machine Parts; Rubber Stressed in Shear by Vertical Load.

Placing the rubber between two steel disks equipped with mounting means results in a mount that can be used as a tension unit for suspending a load to be isolated, as a compression mount under a motor or other device, or as a shear-type insulator.

A type of mount used in electronic and similar equipment consists of a flat rubber ring fastened at the edge in the circular opening of a metal piece and having at its center a metal washer or tube through which a bolt can be run.

By making a thin sandwich consisting of two strips of steel with rubber between, a vibration-absorbing shim is produced. It is used as a cushioning element beneath lathe tools.

When a cylinder of soft rubber is vulcanized to a tubular- or solid-steel core and to a steel outer shell, there results a suspension unit that may eventually affect all motorcar travel. If the core is mounted

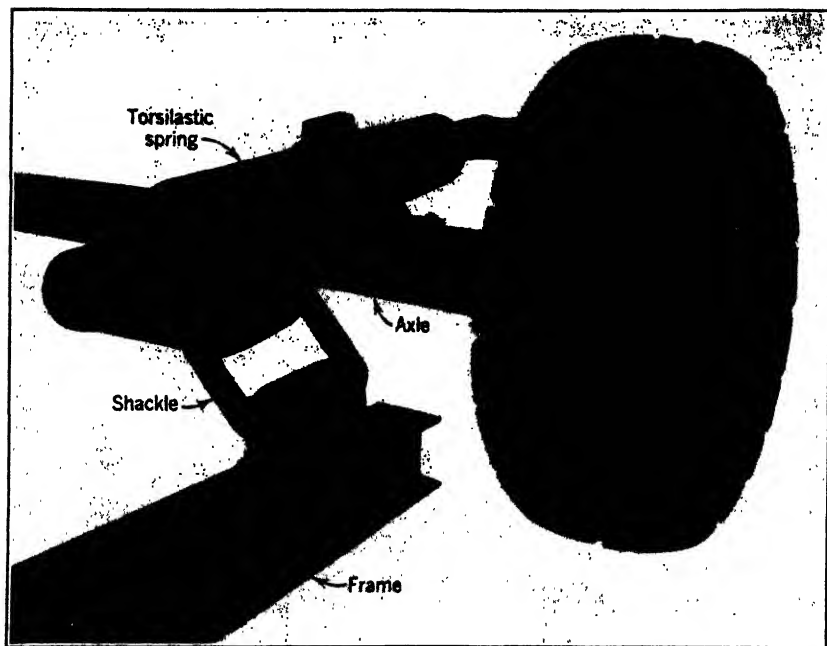


FIG. 21-11. Torsilastic Spring, Showing Arrangement of Cylinder of Soft Rubber Sandwiched between Steel Outer Shell and Steel Core Equipped with Torsion Arm.

solidly, and a torsion arm is attached to the outer shell, pressure on the arm causes the shell to rotate around the core, the intervening rubber being deflected in torsional shear. This is the fundamental principle of the Torsilastic Rubber Spring, many thousands of which were used on tanks and other combat vehicles during World War II. The Torsilastic spring is being used on buses and trailers, and is adaptable as a mount for industrial equipment, farm-machinery seats, and even as a hinge for doors (as on landing ships during the war).

When the moment-arm length in inches is multiplied by the supported load in pounds, the product is the torque or loaded moment of a Torsilastic spring. If the weight supported by the moment arm is set

in oscillation, it behaves like a pendulum weight or one suspended by a coil spring. Dynamic torsional rate is computed by the formula.

$$\text{Deflection (in inches)} = \left( \frac{188}{\text{oscillations per min.}} \right)^2$$

Deflection is the arc length traced by the moment arm in supporting the average moment.

Suspension design and hardness of the rubber in a torsional spring affect the static shear stress as measured between rubber and metal core or shaft. Typical stresses are 60 psi for factory machines and twice that amount for passenger automobiles.

There are many other rubber and rubber-like plastic products which might be classified as laminated structures. These include the automobile tire casing (rubber, fabric, cord, and bead wire); supported Koro-seal upholstery sheeting (plasticized polyvinyl chloride and cotton fabric); boots and other footwear (rubber and fabric); inner-tube repair gum (layer of uncured rubber combined with layer of vulcanized compound); some types of electrician's tape, such as Two-in-One Tape (rubber and fabric); engraving rubber used in making plates for printing cardboard boxes and so on (rubber and fabric); and some types of packing material, such as sheet used for making diaphragms (rubber and fabric plies).

## Molding Laminates and Sandwich Materials

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Molding of laminates and sandwich materials, as might be expected, is an extension of the older art of high-pressure molding.<sup>1</sup> The emphasis is, however, on accomplishing the joining together of the laminas or members in such a manner that all components work together to furnish a predeterminable performance of the desired physical properties.

In order to understand the molding of laminates and of sandwich materials of the class in which we are particularly interested, it is well to review the plastics molding and laminating processes generally.

### DEFINITIONS, PRESSURE RANGES

There has been some confusion of terms, but molding is properly reserved for forming parts or structures with curved surfaces, whereas laminating without further description implies a flat sheet as the finished product. Naturally such a distinction is somewhat arbitrary but helps simplify discussion and thinking and is more or less supported by habitual practice. For example, flat sheets could be but rarely are formed from reinforcing agents that are not first in some prefabricated form such as paper, fabric, mats, processed veneers, or metal sheets.

Looking at molding and laminating broadly, we find that pressures range from about 3000 down to 0 psi. An arbitrary but generally accepted division of the art can be made according to Table 22-1.

Methods of producing pressures over the range given in the table vary from high-pressure oil or water pumps through direct steam pressure to vacuum pressure and, as suggested, in extreme cases, simply the weight or surface tension of the uncured assembly.

TABLE 22-1

Psi	
3000-1000	High-pressure molding and laminating
1000- 500	Intermediate-pressure new positive-die molding
500- 100	Low-pressure laminating; the "plywood" range
100- 25	Low-pressure molding
25- 0	Vacuum-pressure and contact-pressure molding (a variation of the latter is dead-weight molding or laminating)

Tooling or dies range from strong steel platens or mating male and female die parts through combinations of hard-rubber pads or plugs and steel or other high-strength-alloy platens or mold-to-wood forms and rubber bags. With reference to the table on the arbitrary division of pressure ranges, the following are accepted tooling practices for each range:

The 3000-to-1000-psi range<sup>5</sup> makes use of heavy steel platens in massive hydraulic presses for laminating flat sheets. For molding, heavy accurately machined and highly finished mating steel dies are necessary. These, in turn, are placed in a massive hydraulic press which is arranged for quick closing. It is in this range that most of the laminates and moldings known before World War II were made.

In the 100-to-500-psi range, we find very little flat work being done. Lighter accurately mating steel or high-strength-alloy dies and lighter faster-operating presses are used to take advantage of certain high-pressure-type molding compounds modified to improve flow at these slightly lower pressures. These improvements coupled with such modern devices as radio-frequency electrostatic preheating are directed toward faster more economical production.

In the very important range of 500 to 100 psi both flat laminates and molded objects are produced. This is known as the "plywood range."<sup>2,4,12</sup> Hydraulic presses (Fig. 22-1) for flat laminates are generally specially adapted plywood hot presses. Platens and press frames are of medium weight and strength compared to the more massive high-pressure presses. So-called "stress-frame presses" which are easier to build and more compact can be used advantageously in this range.

Molded sections are made by two methods. One of these is borrowed from the hydropress techniques for forming and cutting of aluminum and magnesium sheet, in which one part of the die system, either male or female, is made to accurate contour generally of steel, die-block stock such as Presdwood, Compreg, Papreg and rock maple, or high-strength alloy, whereas the other part is a hard rubber plug with the approxi-





FIG. 22-1. Hydraulic Hot Press of Type Used for Manufacture of Plywood, Sandwich Constructions and Low-Pressure Laminates.

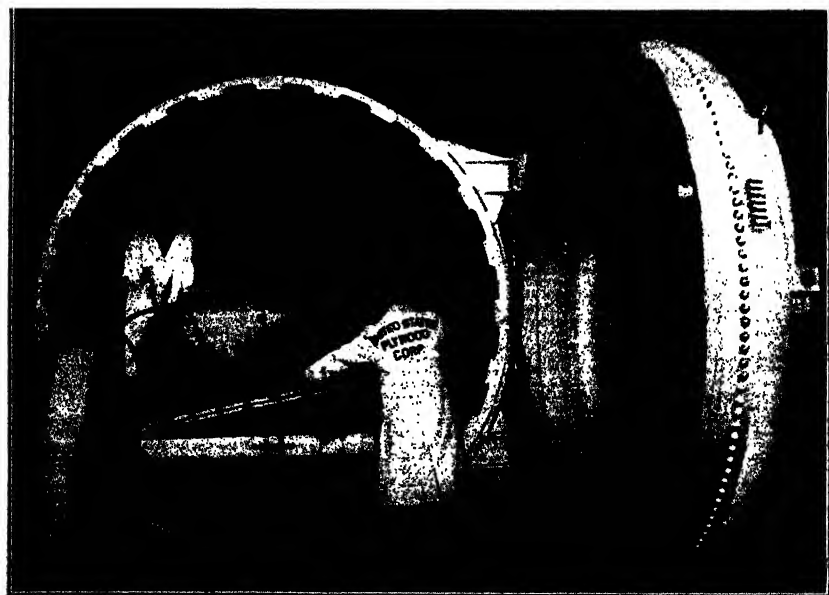


FIG. 22-2. Autoclave 8 by 35 ft Used for Low-Pressure Molding of Curved Constructions in Plywood and Low-Pressure Laminates. Note cooling spray pipes and molding bag vents.

mate contour of the article required. The other method makes use of light but sturdy mating metal dies and correspondingly lighter and lower-cost hydraulic presses. Machining and finishing must be of highest quality, although accuracy of mating can be substantially lower. This process is a form of die molding known as positive die molding, and borrows from both high- and low-pressure procedures.<sup>30</sup>

The range 100 to 25 psi requires but light platens, generally with rubber pads for flat work. For molding, fluid pressure acting on membranes or flexible bags which in turn bear against patterns, either male or female, making use of alloys, plastics, plaster, or wood, are required. Since the fluid pressure must in some way be confined, either an autoclave (Fig. 22-2) or a unit cooker is required, except in the special case of the female mold or pattern which is fitted with a cover and makes use of an inflatable rubber bag, similar to the bladder in a football.<sup>5, 6, 8, 9, 10, 11, 12, 15, 21, 27</sup> It is in this range that molding plywood for boat hulls and aircraft parts and the like is done. This is also the range used for the production of the many thousands of wartime radomes and other special moldings that for one reason or another were not readily made by older higher-pressure techniques<sup>32</sup> (Figs. 22-3 to 22-6).

Tooling for the 25-to-0-psi range in the case of flat laminate production is generally a single light platen which can be used with or without a flexible bag. For molded work, patterns or forms such as are used in the 100-to-25-psi range may be used with or without a bag. If surface tension forces are all that is required to make a molding, no bag is necessary. The possibility of this will depend largely on the nature of the resin and the stiffness of the fabric or reinforcing agent to be molded. For vacuum<sup>28</sup> or light positive pressure some type of envelope which may be rubber, synthetic-rubber rubberized fabric, or polyvinyl

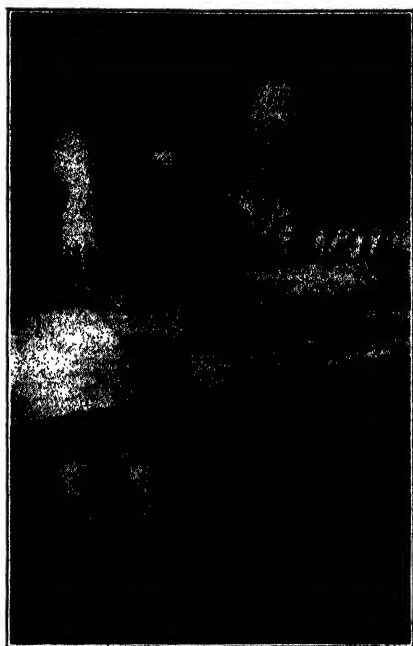


FIG. 22-3. Basic Procedure Used in Laying Up Veneers in Molding Plywood.

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alcohol is used.<sup>20</sup> It should be noted that the new continuous-laminating machines for flat laminates making use of polyester resins or special phenolic resins exert average pressures in this range.<sup>18</sup> These new resins have made such a process practical.



FIG. 22-4. Molded-Plywood-Wing Leading Edge.

### TEMPERATURES

Temperatures required throughout the range are dependent principally on the type of resin involved rather than the pressure. This is obvious when one considers that molding or laminating almost always involves the act of completing the formation of a resin known as "curing," preceded by softening which causes the resin to

flow. Since these phenomena are time and temperature functions, pressure only indirectly dictates the temperature requirement. General practice is to use temperatures with the classes of resins outlined in Table 22-2.



FIG. 22-5. Molded-Plywood Training-Bomber Fuselage. Note the integral molded rib structures.

It should be remembered that the temperatures listed in the table are to be considered as those existing "within the laminate or in the molding" rather than ambient temperatures. It is obvious that within certain limits resins from a lower temperature class can be used at higher

TABLE 22-2

450°F	Lignin and silicone resins
310°F	Cross-linked thermoplastics
290°F	Alkali-catalyzed phenol-formaldehyde resins, two-stage neutral phenol-formaldehyde resins
180°F and 290°F	Polyester resins. 180°F is used for gelation of the resins and 290°F to complete the cross linking, because in the monomeric form these materials are often substantially volatile at the final curing temperature, and loss of monomer will unbalance the resin. After gelation has set in, this loss will not occur.
190°F	Melamine-formaldehyde, urea-formaldehyde, "fortified" urea-formaldehyde, certain acid-catalyzed phenol-formaldehyde resins
75°F to 120°F	Resorcinol-formaldehyde, phenol-resorcinol-formaldehyde, acid-catalyzed casting-type phenol-formaldehyde, catalyzed melamine-formaldehyde resins
70°F	Room-temperature-setting urea-formaldehyde, resorcinol-formaldehyde, certain furfural resins

temperatures with resulting shorter cures. It is likewise obvious that very high-speed processes can make use of temperatures possibly as high as 1000°F if the effective temperature in the laminate is correct and the part is such that heat flow is no problem. As cures are made shorter and shorter by the use of higher and higher temperatures, it will be found that, other things being equal, each resin has a limit beyond which one cannot go without experiencing frothing, burning, or excessive cross linking with loss of strength.<sup>3</sup>

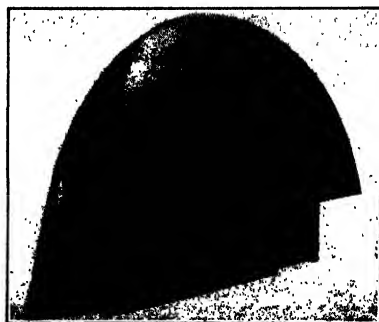


FIG. 22-6. Molded-Plywood Wing-Tip Edge.

## TIME

As has been suggested, time is the other of the two vital factors controlling the cure or the flow of the mass being laminated or molded. Time varies, depending on the following existing conditions:

The amount of mass to be heated.

The rate of application of heat and whether heat is applied from one or both sides of the part.

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Rate of heat conduction of the mass or assembly.

Time necessary to complete the flow, and chemical action.

Periods involved may be as short as a minute or as long as an hour or more.

With this picture of the whole field of molding or laminating before us, we will now deal specifically with the techniques of molding of laminates and sandwich materials with particular emphasis on those types engineered to produce predetermined sets of controllable physical properties.

### **METHODS OF LOW-PRESSURE FORMING OF LAMINATES AND SANDWICH MATERIAL**

#### **DEFINITIONS**

Since low-pressure forming of laminates and sandwich materials is a new art and a new industry, it would be well to start with a definition of the principle terms. Earlier in this discussion, the term "low pressure" was given broadly as any value of laminating or molding pressure between 500 and 0 psi. This convenient and arbitrary definition is derived principally from a consideration of equipment necessary.

Forming is an obvious term which includes the making of both flat sheets and curved parts. Laminating may or may not be involved in the strict sense but generally is. Laminating, often used interchangeably with molding, indicates that the unit is formed from a series of laminas or layers which are welded into one piece by the action of heat and pressure on the impregnating resin contained in the laminas. Laminating generally carries the industry connotation that a flat piece is being made. Molding similarly indicates that a curved part is being made, although neither term is used strictly as indicated.

Considerable study has already gone into the definition of a sandwich construction or sandwich material,<sup>31</sup> as it is obvious that there are many types of sandwiches in common use with which we are not concerned. In this industry, a sandwich material is generally considered to be composed of relatively dense high-strength skins which are relatively thin and permanently affixed to either side of a central core material which is relatively thick and relatively of low density. Although a sandwich representing the reverse of these requirements could be constructed, it would have little value as a structural material. In the sandwich constructions under consideration, both the skins and the

core are generally fabricated in advance and then combined to produce the sandwich.

Laminations or laminates are composed of layers of laminas generally uniform and identical to each other with respect to thickness, density, and strength. The individual laminas or plies are generally relatively strong so that the resulting composite is merely a combination of the individual properties.

#### CHOICE OF PRESSURES

There are a number of important reasons justifying the use of low pressure in producing laminates and sandwich constructions. These constructions are almost invariably for strength or structural purposes. In solid laminates and in the skins of sandwiches the filler or reinforcing fabric furnishes the strength characteristics, whereas the resin or the adhesive holds the construction together. The requirements of these constructions are that they be of uniform strength, stress-free, and flat or of accurate contour. There must, therefore, not be any crushing displacement or deformation due to the forming pressure.

Sandwiches, in particular, owing to the low density of the core materials, must be assembled with low pressure not only to meet the foregoing requirements, but also so that the internal construction of the core is not buckled or distorted, or prestressed.

Finally, the large areas of a unit or a panel normally required would necessitate excessively heavy and costly equipment, if high pressures were to be used.

In discussing the actual methods used, consideration will first be given to producing flat laminates; then curved laminates followed by flat sandwich constructions; and, finally, curved sandwich constructions.

#### PREPARATION OF MATERIALS

Since flat laminates are, as was noted in the definition, the result of the joining together of separate layers, called laminas or plies, attention must first be given to the preparation of the stock of which these layers is composed. Each layer comprises a reinforcing sheet, fabric, or bat which has been appropriately treated with a resin material that will later secure it firmly to its neighbors and hold each individual fiber in place. The reinforcing sheet must, therefore, be treated by some means which will attach to it in a convenient manner for subsequent handling the necessary resin. This procedure can involve simple saturation of the web or reinforcing sheet by passing it through a bath, or coating of

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the outside layers without much penetration. For special purposes, true impregnation in addition to superficial saturation or coating may be required, and the simple deposition of dry powdered resin followed by sintering to make it adhere has been used successfully.

Since the stock so prepared is generally treated with a resin in solution, it is necessary that it be dried before further use. This drying must dispel as much volatile solvent as is possible without causing cure of the resin. If the volatile solvent is not removed, the roll or pack of treated stock may flow together and form a solid block which is quite useless. This phenomenon known as "blocking" must not occur under any reasonable storage conditions.

During the drying operation, it is often desirable to initiate the advancement of the resin toward the cured condition. An unadvanced resin may flow excessively under the conditions of lamination or may volatilize from the heat with the result that the finished laminate will be starved and will not have sufficient binder to resist delamination under stress.

Finally, the resin must be so chosen and so treated that the impregnated reinforcing sheet must be stable for the necessary period of storage until it can be used.

### PRODUCTION

**Assembly.** The first step in the actual production of the laminate is the lay-up or assembly of the laminas or plies of prepared reinforcing fabric or fiber. For flat rectangular sheets this merely means cutting to length and width, slightly oversize, to allow for accurate trimming to size and stacking the proper number of layers to give the required final thickness. If the laminas are anisotropic, it is often desired to cross-band the assembly. This means that alternate layers are cut so that they can be turned 90° with respect to the other layers so that a balanced panel with equal strength on either axis is obtained.

If the panel is of odd shape, it may be more economical to lay up templated sheets than to cut the finished part from a rectangular laminate. Such templating can be done by means of steel-rule dies and can be made a very economical operation.

If the panels are larger in any dimension than available sheet stock will produce, it becomes necessary to decide whether each layer will be pieced by means of a lap or a butt. Both have their advantages and disadvantages, so that individual requirements should dictate the chosen practice. Generally laps will give the greater strength but less

accuracy or uniformity in thickness, and butt joints are just the reverse.

In order to obtain a maximum of strength it is important to avoid wrinkles or slack in each layer. Ideally, each layer should be stretched taut on both axes until the moment lamination or resin cure actually begins. However, if the stock has been properly handled up to the point of lay-up, adequate performance will be obtained from the laminate if ordinary care is used in stacking the individual sheets.

**Pressing.** After the lay-up is completed, it is necessary to press or form the laminate. The curing cycle must be chosen with regard to the requirements of the resin used to impregnate the sheet with respect to both time and temperature. Sources of pressure were given earlier in this discussion and should not need repetition here except to indicate that the hydraulic press is the most common source for large volume production, although certain of the newer laminates are now being made in a continuous-laminating process, in which rolls furnish the pressure. The heat is, of course, furnished by means of steam, hot oil, electrical-resistance heating, radio-frequency electrostatic heating, and occasionally by means of radiant-heat lamps, often called infra-red lamps.

Precuring and bridging must be avoided if a sound laminate is to result. Precuring most commonly results from too much exposure to heat before the pressure is applied, and the remedy is obviously to shorten the time required to load the press. For a multiopening press and a fast-curing laminate, it may also be necessary to place the assemblies for the bottom few openings on insulating cauls in order to retard the application of heat. Bridging which is a form of precuring occurs in thick laminates wherein the outer layers become hard and inflexible before the center has heated to the fusing point of the resin. Bridging has the effect of removing the pressure from the central layers so that they will not be well pressed together and in extreme cases may actually be loose. The remedy is to reduce the thickness of the laminate or to make use of radio-frequency electrostatic heating in which the problem of heat flow through the laminate does not exist.

It is important that the assembly being cured does not adhere to or contaminate with resin the pressing platens.<sup>33</sup> It is general practice to include metal cauls above and below each assembly which are, in turn, lubricated with parting agents. These parting agents include metallic soaps, certain petroleum-oil fractions, certain vegetable-oil fractions, and silicone greases. It is possible to apply the parting agent directly to the pressing platens, but, since the platens are generally heated con-



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tinuously, the parting agents will tend to burn off, and recoating is simpler in the case of the detachable caul. In some cases, the resin manufacturer will formulate the parting agent into the resin so that little or no additional material need be added to the cauls or press-platen surfaces, once these surfaces are "broken in."

Blisters are a common fault particularly in the formation of flat laminates, and they are most frequently caused by residual volatile solvent not properly dried out at the time of impregnation or by too high a proportion of volatile resin component. The only real remedy is, of course, to treat the impregnated web properly.

If susceptibility to blistering is expected, certain laminates can be made successfully by making use of an expedient known as "breathing the press."<sup>36</sup> This operation involves reduction of press pressure for a brief period after the charge is thoroughly heated but before curing has set in or all flow has ceased. The aim is to release the gases formed by the heat from the excessive quantity of volatile material but at a rate low enough to avoid explosive release and rupture of the partly formed sheet. For some laminates pressure is only reduced to the point where it is in equilibrium with the gas pressure of the volatile involved at the pressing temperature. For still others the pressure is just reduced to zero, but any opening of the press is avoided. For very porous plies the press can actually be momentarily opened but must be reclosed as soon as possible.

Starvation has been described above. It is a fault due to excessive flow of the resin under pressure and results in a weak laminate just as surely as would an underimpregnated stock. The resin may squeeze out or disappear into the plies if the latter are of the surface-coated type. Lowering press pressure below normal is a suitable expedient, but proper preadvancement of the resin after impregnation is the correct cure. For resins that cannot be preadvanced a two-step curing-temperature cycle is necessary.

**Discharging and Stacking.** Discharge from the press may be hot or cold, depending on the requirements of the resin used. Thermoplastic resins must generally be discharged cold for the obvious reason that during lamination they are above their melting point and, if they are discharged hot, they will either delaminate or deform during handling. Certain thermosetting laminates, particularly of the decorative type, require some cooling before discharge if the best possible finish and perfect flatness are required.

When discharging hot from the press, it is well to adopt one or two preferred procedures in order to assure reasonable flatness. One of

these commonly used is known as "dead piling." This, as the name implies, simply means piling the hot panels one on top of the other when they come from the press, until a stack is built up. This stack when properly covered will, of course, cool down very slowly, and stresses are thereby minimized in a kind of annealing action. A certain small percentage of the curing time required for the resin can be subtracted from the press time and completed during dead piling as there is often enough sensible heat remaining in the pile to complete the cure. Obviously, it is wise to be sure that dependence on the heat in the pile is not carried too far.

An alternate method advisable where rapid cooling is necessary is known as "finger racking." The panels as they come from the press are supported in such a manner that the room-temperature air has equal access to the whole area on both sides of the panel. This results in rapid uniform cooling, and, if the construction is reasonably well-balanced, it will produce satisfactory flatness.

**Finishing.** Final steps in the production of the product are, of course, trimming and inspection. Inspection procedures are more or less obvious and are hardly within the scope of this discussion, but a word or two on suitable tools for trimming may be in order. High-grade woodworking tools perform reasonably well when used on plastics in which the reinforcing agents are cellulosic in nature, but they have a rather short life. Better production economy and less maintenance results from the use of at least nonferrous-metal working tools or preferably high-speed steel tools.<sup>26</sup> For plastics reinforced with glass fibers, asbestos, or other mineral reinforcing agents, high-speed steel tools are suitable, but better life is obtained with Carboloy-tipped tools or diamond-tipped tools and saws. The rate of production, the quantities handled, and the amount of maintenance required, must all be balanced against each other in determining the most economical type of operation.

#### RADIO-FREQUENCY HEATING

Radio-frequency energy as a source of heat,<sup>14, 16, 18, 19</sup> as noted previously, is indicated particularly where thick assemblies are involved or where it is desirable to avoid any delay having to do with heat transfer. Radio-frequency energy in an electrostatic field generates heat uniformly throughout most plastics. Furthermore, it does it very rapidly in all cases except those few plastics which are extremely efficient insulators, such as polystyrene, polytetrafluorethylene and polyethylene. Radio-frequency energy can be used to cure thin laminates

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by placing multiple assemblies suitably separated in the radio-frequency field. This procedure is likely to be of doubtful economic value if it must compete with quick-acting hydraulic presses or continuous roll-type laminators. Thin laminates of relatively large surface area are very difficult to cure by means of radio-frequency energy because of the hazard of flashover from one electrode to the other which results in erratic operation of the equipment and burning of the laminate.

A desirable use for radio-frequency energy in the curing of thick masses or thick sections is as a means of preheating.<sup>24</sup> The sections ready for curing are placed in the field and brought to curing temperature, advantage being taken of the rapid action of radio-frequency energy. The specimens can then be transferred to a hot press or an oven in order to maintain the temperature since all the hot press or oven has to do is take care of heat losses. Often this procedure is easier and more reliable in production than completing the cure by means of radio-frequency energy. Since the amount of power required to bring the specimen up to temperature is very high compared to the amount of power required to keep it warm once the temperature is reached, the radio-frequency equipment cannot be kept operating at maximum capacity and, thus, maximum economy, unless the equipment is used simply as a preheater. It is not always possible to take advantage of continued application of high power, allowing the temperature to rise far above normal curing temperature, and, thus, effect extremely short curing periods, because charring in the center is very apt to take place, and indeed even explosions may occur, owing to the generation of high gas pressures in the center caused by the development of excessively high temperatures in thick masses. This occurs, because most resin-curing reactions are exothermic, and thick sections are good heat insulators. Thus the curing reaction may run away with itself.

In investigating the economics of radio-frequency heating it is well to bear in mind another point. In any curing procedure where there is an appreciable percentage of water, say, as much as 10 per cent, it is advisable to use resins which cure below the boiling point of water, for, if it becomes necessary to pass through the boiling point, it will be found that the energy required simply to get rid of the water will be as much as four times (and sometimes more) the total energy required to raise the mass without the water from room temperature to a curing temperature of 290°F.

It is generally safe to say that, once an operation involving radio-frequency electrostatic heating has been properly set up, any reasonably skilled help can operate the equipment day in and day out and

obtain satisfactory results. On the other hand, the individual electrode problem must not be underestimated, and it is wise to have access to the advice of a competent radio engineer with experience in this field, in order to assist in deciding whether or not a proposed operation will be economical, and to help in the solution of the electrode problem, without which there simply can be no worth-while result.

#### CURVED LAMINATES

In considering the production of curved laminates it is convenient to divide the discussion, dealing, first, with the production of simple curvatures and, finally, with the production of compound curved parts, for, although the technique for making compound curvatures is applicable to simple curves, there are certain simplified procedures suitable only for making simple curves.

**Postforming.** Of relatively recent popularity is the technique of producing simple curves by means of postforming.<sup>28</sup> \* Wood has been bent for years by means of heat and moisture, and, of course, certain time-honored molding processes for dealing with thermoplastics could be classified as postforming, but not until recently have flat sheets based on thermosetting resins been so treated. There are two classes of thermosetting resins particularly suited to postforming. One of these classes makes use of the two-stage phenolic resins which are applied to the web for the production of the stock flat laminate from alcohol solution. Any low-molecular-weight or water-soluble material is carefully avoided. The laminates are truly heat-hardened and generally considered completely cured, although minimum temperatures are to be preferred, and occasionally judicious undercuring is helpful. These laminates, if then subjected to an additional 25 to 50°F of temperatures over their original curing temperature, can readily be bent to curvatures following surprisingly small radii and, within certain limits, can be drawn. As might be expected, the nature of the reinforcing fabric has some effect on the success of the operation, particularly as far as drawing is concerned. For best results the forming fixtures should be well engineered, and it is desirable that the clamping action of the hold-down member of the fixture be adjusted so that it is applied at the proper time and in the proper position to prevent the extreme stressing of the fibers at the outer or tension side of the bend. Application of tension to the extreme ends of the stock while drawing around the form is of considerable assistance in relieving undue

\* See Chapter 6 for a further discussion of postforming.

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stresses on the fibers. Of course, the form around which the stock is bent must be heated to the desired additional temperature even though the stock may be preheated. Occasionally it is necessary to heat the hold-down as well.

Partial and occasionally complete cooling in the fixture is necessary to avoid spring-back and loss of shape while hot. An excellent compromise which avoids tying up the bending equipment during cooling is to transfer the hot part to a fixture which will hold it to the required curvature while it cools, but which can be a much simpler device since the bending operation has already been accomplished.

Another type of resin that is suitable for postforming is the group known as compound copolymers or polyesters. These resins in passing from the liquid to the solid stage pass through a gel condition which is sufficiently stable to allow some handling. As a result, the laminated stock can be brought to the gel stage but not completely cured. It can then be reheated and bent to the desired curvature, and cross linkage can be completed which will render the resin hard and substantially infusible. Since not all the resins of this family have a very pronounced gel stage, some care must be used in choosing the best resin for the purpose.

The disadvantages of postforming are that, with the exception of modest draws, it is limited substantially to simple curves and the finished part is not stress-free. There are all too frequently incipient fractures in the laminate and torn reinforcing fibers which make for weakness in the structure. Whether or not these weaknesses will be serious will, of course, depend on the use to which the finished part is to be put.

**Compound Curves.** Parts of substantial compound curvature must, of course, be molded. As in the case of the flat laminates, once the coated or impregnated stock is properly prepared, the first step is the lay-up. Since we are concerned with low-pressure molding which we wish to be stress-free and to be an assembly of laminas of known critical performance held together so that each can co-operate with the other, we must remember that care in the lay-up is extremely important. If the operation as a whole is considered one of gluing laminas to contour, it is easier to visualize why care is important. Thus we must template properly, cut the necessary gussets, decide on and properly locate and distribute the types of joints and avoid wrinkles or slack as much as possible. The preparation of the actual stock including the preparation, drying, and handling is, of course, identical with that for the production of flat laminates.

It is comparatively simple to lay up the laminas for a thin section tightly and free from wrinkles or slack, but for a thick section serious problems arise because the outer layers do not occupy the same position after lay-up and before compression that they do when molding is complete. In the case of a male mold, the outer layers cover less area after compression than before, and there is a great tendency for wrinkles to occur. In the case of female mold or cavity, the reverse is true, with the result that tearing is apt to occur. In order to minimize these defects, very thick sections must be molded in steps. For example, if  $\frac{1}{2}$  in. of laminate is required, it may be necessary to mold this in two, three, or four steps, in which case it may also be found necessary to include, as an outer layer, a sheet of reinforcing fiber or fabric that is unimpregnated, which serves as a "gluing layer" so that the subsequent molding is thoroughly bonded.

In molding thick sections, radio-frequency electrostatic heating has often been proposed, and no doubt it can be made to prove its worth, provided it is remembered that radio-frequency equipment furnishes heat only and not pressure. Thus, there is the triple problem of properly locating the electrodes with respect to the piece to be cured so that application of pressure is not interfered with, so that arc-over and puncture do not occur, and, finally, so that one electrode, at least, is reasonably well insulated from the charge so that heating by conduction currents can be prevented.

The forms or dies required almost always call for a definite and an indefinite member. The definite member is a male or female pattern or form, and the indefinite member is a flexible membrane or bag or, in one case to be discussed later, a semihard rubber plug. The definite member can be of wood, plaster, laminated plastics, low-melting alloys, sheet metal, or cast metal. Wood is, of course, built into a pattern in the usual fashion. Plaster similarly needs no special treatment beyond possibly wire or coarse fiber reinforcement and occasionally phenolic-resin surface impregnation. Low-melting alloys can be used in two ways. They can be cast to the approximate dimensions and machined, but a simpler and more interesting use is to force into a pot of low-melting alloy a suitable wood or plaster pattern and allow the alloy to freeze. On removal of the pattern a little finishing is all that is necessary to put the cavity to use. The pot in which the alloy was originally melted can be jacketed for oil heating. By lowering the temperature of the heating oil a safe distance below the melting point of the alloy, heat necessary for the cure of the resin can be introduced. After the mold has served its purpose, it is simply necessary to remelt

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it to produce another shape. Sheet-metal forms can be spun or hammered, and both these techniques have proved valuable in the quick production of low-cost tooling. Generally supporting rims or frames are necessary to protect sheet-metal forms. Cast-metal forms of bronze or steel or aluminum are the most permanent and the most costly and can only be justified for large runs.

The indefinite member can be a vented bag as used in connection with the autoclave or a simple vacuum bag or a pressure bag which is used in the same manner as a football bladder. It can also be a rubber plug or an incompatible liquid. Most of these devices are obvious from their name, but the rubber plug needs some additional identification. The aircraft industry forms aluminum and magnesium in huge presses called "hydro presses" using a metal shape and a plug of semihard rubber. Advantage is taken of the fact that rubber acts like a fluid when it is completely confined. It has the additional advantage that, until the moment it is completely confined, it will exert pressure only at high spots which can thus be chosen so that wrinkles and tearing can be avoided. This procedure is quite applicable to low-pressure molding using softer rubber and, of course, less sturdy molds and lighter presses. Incompatible liquid molding is relatively new in a new art. The cavity with the uncured laminas in place is filled with a liquid which can be heated and which is not compatible with and does not interfere with the curing of the resin. If the relative surface tensions of the resin and the incompatible liquid are correct and if the reinforcing material or fabric is sufficiently fine-grained in construction that the incompatible liquid will not be forced through the pores, very creditable moldings of complex shapes can be accomplished. Since the pressures applicable in this process are sharply limited, the so-called contact resins should be used. Obviously, certain of the very low-melting alloys are indicated for this procedure.

A hybrid low-pressure molding process borrowed from high-pressure compression technique is casting molding.<sup>25</sup> It takes two forms. The more important of these consists of laying up unimpregnated fabric on or in an appropriate form, pouring resin monomer or resin "sirup" or varnish over the fabric, taking care to have a slight excess, and then lightly forcing a mating form into position.<sup>27</sup> This last step squeezes the resin through the fabric, displaces the air, and floods the molding space between the two dies. After cure is completed, a highly satisfactory and very finished piece of work results.

In designing the tooling for any of these specific techniques it is, of course, important that there be a molding exit and that the form have

sufficient draft so that it is not excessively difficult to remove the finished part. Certain complex parts that do not permit a normal molding exit must be handled by means of collapsible male mandrels or split female mandrels that can be disassembled for part removal. Finally, some thought must be given to thermal expansion and contraction of the mold material as compared to the plastic which will be molded, since it is quite possible to develop a shrink fit between the mold and the part which precludes removal of the part. This is particularly true if the draft must be very small.

**Sources of Heat and Pressure.** Sources of heat are saturated steam, hot oil, radiant energy, also called infrared ray heating, hot-air oven heating, and radio-frequency electrostatic heating. Sources of pressure are steam and mixtures of steam and air, simple vacuum, hydro-press, or simply hydraulic presses where rubber is used as the fluid or where casting molding is used and it is desired to have a positive force to close the dies. Finally, there is the dead-weight method of producing pressure which includes the special case of low-pressure molding wherein surface tension of the resin binder holds the uncured laminate in position until cure is completed.

Cure, trimming, finishing, and inspecting are generally similar in requirements to those of flat work and need not be repeated here.

#### PRODUCTION OF SANDWICH MATERIALS\*

Perhaps the most important new construction in the postwar field which makes use of low-pressure techniques in its production is the sandwich construction. By far the largest part of this work, it appears at the present time, will be in flat panels. Thus, in this discussion most emphasis is placed on the methods of producing flat assemblies, although, for the sake of completeness, curved assemblies are included in the final section. In considering sandwich constructions, in general, it is well to start with a résumé of the purpose of each component.<sup>29, 34</sup>

A sandwich in this field under discussion consists of relatively thin high-strength relatively high-density skins on either side of a relatively thick relatively low-density weak core.<sup>31, 35</sup> In addition to the two main components of a sandwich, there is the very necessary adhesive<sup>7, 22</sup> required to attach the skins to the core, the auxiliary adhesives necessary in other parts of the assembly which are described later, and the rails or edge banding. The edge banding is often neces-

\* See Chapter 20 for a discussion of sandwich materials.



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sary for protection or for joining of one or more sections to produce a large panel, or for attachment. It is pretty generally understood that the core performs the simple function of keeping the skins separated a chosen distance and in a fixed position relative to each other, at the same time desirably contributing as little weight as possible to the finished assembly. The core is thus said to stabilize the skins. The skins in turn furnish the strength and, to a large extent, the inherent engineering characteristics that can be expected.

**Skins for Sandwiches.** Skins are generally made of metal (most often aluminum), stainless steel, high-strength laminates (made by processes already described), plywood, and combinations of these four.

**Cores for Sandwiches.** Currently popular core materials are end-grain balsa wood, hard sponge rubber, cellular cellulose acetate, foamed thermosetting resins, and honeycomb construction. Rails or edge banding include metal both solid and in structural forms, laminates, plywood, and solid wood or dimension stock.

**Adhesives.\*** The adhesives used are primarily those required to attach the skins to the core and secondarily those which may be required in the assembly of the core, the assembly of the rails and in the attachment of the core to the rail. These adhesives<sup>7, 22</sup> vary in chemical nature all the way from simple thermosetting resins used ordinarily in wood bonding to polyfunctional adhesives that adhere to metals and nonmetals equally well. In between are bonding processes, discussed later, in which both types are used in a procedure known as "two-step bonding."

Incidental to the production of sandwich panels are the inserts or blocks which are generally similar in construction to the edge banding or rail. These blocks are, of course, necessary for the attachment of fittings, since it is obvious that one cannot bolt-screw or rivet to a sandwich panel as one would to a piece of sheet steel or wooden planking.

**Production Procedures.** In describing production procedures, it must first be made clear that each particular combination requires its own procedure. There are certain general rules which can be laid down, but successful production of uniformly strong high-quality sandwiches requires strict attention to detail in every step and a proper choice of procedure, depending on the combination to be manufactured.

Most sandwich constructions can be made following one or the other of two general processes. Either the faces and the completed cores

\* See Chapter 2 for an extended discussion of adhesives.

can first be produced and then finally brought together, or a chronological sequence of steps including the production of one face, the lay-up and attachment of the core to the first face, and the addition of the last face can be followed. In the second of these two procedures the faces are generally, but not always, prepared in advance. The complete core assembly seldom is, although the core stock, of course, is assumed to be on hand.

The important types of sandwich construction are at present plywood faces with balsa core, plastic-laminate faces with sponge rubber or resin cores, metal-faced honeycomb-cored panels, plywood-faced honeycomb-cored panels and metal-faced balsa-core panels. Cellular cellulose acetate which is actually a special case of a resin sponge can be used with plywood or metal faces as well as for plastic laminate faces. Other combinations are obviously possible, but, if one understands the production methods required for popular forms, the necessary procedure for special combinations is easily visualized. There is one possible exception to this statement in which the core is prepared by foaming an appropriate resin in place. It is necessary in this procedure to locate the skins properly with respect to each other in a fixture which will insure maintenance of their positions until the foaming is completed. This process has the particular advantage that it can often be accomplished in a single operation and can be arranged so that an attaching adhesive is unnecessary. Unfortunately, the technique is a difficult one, and the tooling is rather costly with the result that it has not had wide acceptance.

**Balsa Core, Plywood Skin.** The simplest and perhaps the oldest of the currently important sandwich constructions is the combination of plywood skins and a balsa core which was sky-rocketed to fame through its use in the British Mosquito bomber.<sup>17</sup> In the production of this construction the core can either be prepared in advance or laid up on one face after which the second face is affixed. In either case it is necessary to grade the balsa to approximately the desired density, eliminate all the defective sections, and slice to the correct thickness with a little overallowance for later finishing. If the method of preparation is chosen in advance, the balsa slices are laid up in a jig starting at one end and progressing to the other until the complete "core panel" is built. In order that the finished construction can transmit shear forces, the sections of balsa must be edge-glued to each other. This is most often done with a cold- or warm-setting phenolic resin. The completed core section is set aside at room temperature or in a low-temperature oven to cure, after which it is carefully sanded or sliced to

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thickness and is ready for the faces. The plywood prepared in advance and generally to aircraft specifications<sup>12</sup> can be bonded to the balsa core with either a room-temperature or warm-setting adhesive of suitable durability, in which case the assembled panels are pressed in a bale and set aside to cure. Hot-press technique can be used, in which case it is advisable to have stops in the press in order to insure against crushing of the core. The only special precautions which must be exercised are to use an adhesive so formulated so that it will not all be absorbed by the balsa resulting in a starved glue line. Priming or sealing of the balsa may be necessary.

The principle defects in paneling of this construction are lack of flatness, uneven appearance, and, occasionally, a poor bond due to starvation or penetration into the balsa. Lack of flatness generally results from unequal moisture content of the faces at the time of bonding or unequal heating if hot-press curing is used. The remedies are obvious.

If the alternate method of producing these panels is used, one of the prepared plywood faces is first spread, one side with the desired adhesive. The balsa sections are laid on the adhesive while wet and built up in the same manner as described previously for producing the core in a one-piece panel. After all the balsa is in place, the second plywood panel properly spread with adhesive is laid over the balsa, and the panel is baled and set aside to allow the resin to cure. This procedure has the advantage of being a more or less continuous process but does not readily lend itself to hot pressing, and it is very necessary that the individual blocks of balsa be uniform in height and of correct thickness, as there can be no afterslicing or work on the core.

**Sponge Core, Laminate Skin.** The plastic-laminate skin and resin-sponge-core sandwich construction became popular during World War II as a result of the need for radar-antenna housings (radomes)<sup>32</sup> and equipment housings that were light and strong and had some heat-insulating value (Figs. 22-7 and 22-8). Although some of these constructions made use of metal skins, most of them were produced with high-strength plastic laminates generally molded under low pressure. In such constructions it is first necessary to cut off the outside skins of the sponge which are formed during its manufacture, since the skins are of a different density from the sponge itself and generally contain an undesirable parting agent. After the skin is removed and the core is cut to size, the dust resulting from cutting must be blown away, and in some very severe uses the stock must be pretreated by heating in

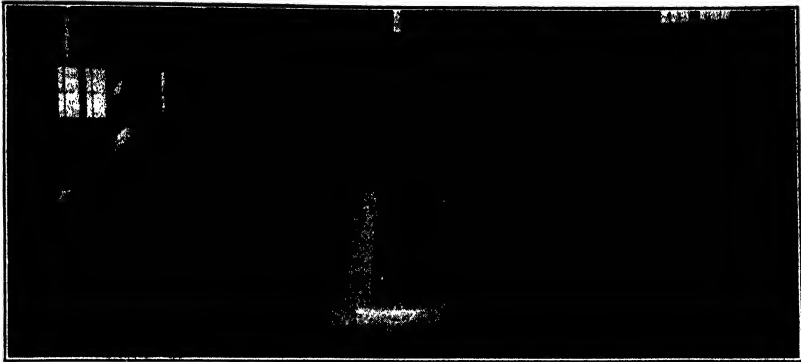


FIG. 22-7. Dome Section of 26-ft Sandwich-Type Combination S and X-Band Radome. Skins are Fibreglas-Polyester Resin. Core is expanded Hycar sponge. An example of large low-pressure molding, requiring dimensional accuracy.

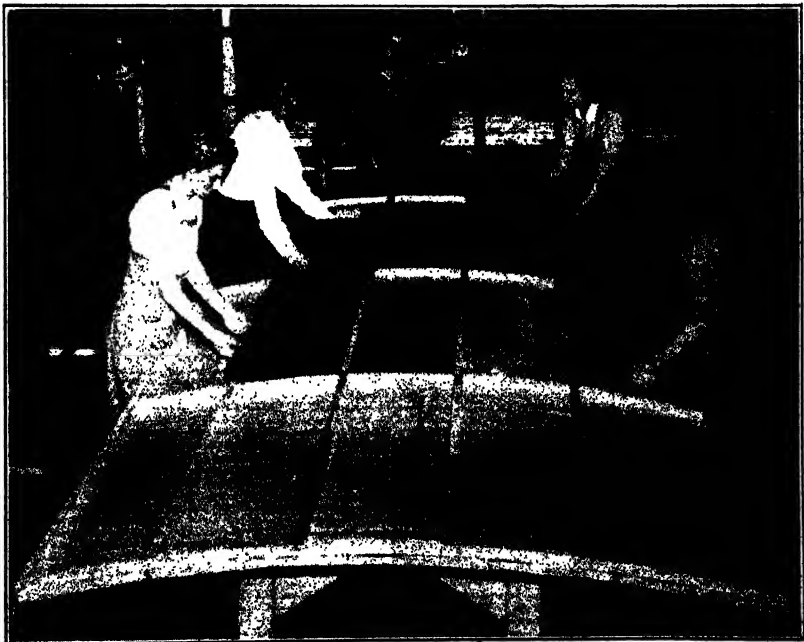


FIG. 22-8. Lay-up Procedure of a Large Sandwich-Type Molded Radome. Material being fitted into place is Hycar hard sponge.

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order to make sure that it will not shrink, swell, or distort under subsequent bonding temperatures.

Lay-up for the two-step method includes lamination and curing of the two skins in advance and cutting and fitting of the sponge core. At the moment of assembly one of the faces with adhesive on its inner side is placed on the lay-up table, and a light frame or jig is laid over the skin for guidance in fitting the core. The jig is not absolutely necessary if the finished panel will have edge rails or banding. If there is to be edge banding, it should be located properly on the lower skin. The sections of core preferably coated with adhesive on both sides are fitted in place much like the balsa, and adjacent edges are coated with adhesive and pressed together to insure a bond that will transfer shear. When all the core is in place, the upper skin coated on its under side with adhesive is laid over the assembly. The completed lay-up is then put under pressure and heat, depending on the requirements of the adhesive used. Stops may be necessary unless the edged banding can act as stops or unless the press is accurately controllable in the very low-pressure ranges.

The one-step process requires greater care but is faster and, under certain circumstances, as in radomes, is necessary for electrical reasons. In this procedure the layers of impregnated fabric are laid up in such a manner as to produce the lower skin. A quantity of adhesive is next applied to the under side of the core pieces which are laid up wet on the un laminated lower skin assembly. When all the core is in place, after it has been ascertained that the edges are firmly forced together and adequately coated with adhesive, the layers of impregnated fabric comprising the upper skin are laid over the core. The whole assembly is then placed in the hot press or in a molding autoclave, and all uncured adhesives and impregnating resins are simultaneously cured. This step forms the upper and lower skins, attaches them to their respective sides of the core, and cures the adhesive used in edge-bonding the core. An edge band can be laid up and scarfed into the core and also cured and attached at the same time. Very careful choice of adhesives is necessary, but this procedure is entirely practical and fast and produces an excellent sandwich.

Defects common to either lay-up are unbonded areas, skin wrinkles, excessively wide gaps in the core, swollen spots, and hollow spots. Most of these defects have obvious causes and obvious remedies. The high spots and hollow spots are generally the result of swelling or shrinkage due to faulty sponge, and these can be avoided by pre-heat treating as previously mentioned. In the one-step process, where polyester resins

are used in the skin laminate, there can also be a defect which leaves a sticky or uncured area. This results from poisoning of the polyester resin due to excessive exposure to air, water, or undesirable compounds exuding from the sponge during the cure. Pre-heat treating will generally eliminate the last-mentioned source of trouble. The others can be prevented by obvious care.

**Honeycomb Core, Metal Skin (Figs. 22-9 to 22-12).** The most important sandwich at the present time is the metal-faced honeycombed sandwich of which perhaps the most frequently used modification is one in which the skins are Alclad and the honeycomb is formed from phenolic-resin-impregnated fabric or paper. There are two generally accepted methods of making such a sandwich, and they center around the methods used for forming the honeycomb. In one case the impregnated fabric or paper is corrugated by means of meshing belts carrying suitably shaped and spaced bars or gears, and the corrugations are glued together at their crests. The other is formed by striping the flat web of paper or fabric at intervals with adhesive, laying alternate pieces of the web so that even-numbered layers have their stripes centered between those on the odd-numbered layers. After the adhesive in the stripe is activated and cured, the pad is sliced into sections of the proper thickness, and the honeycomb is expanded in the same manner as is used in opening a paper Christmas bell.

In the formation of honeycomb by corrugation, impregnated paper or fabric of the same general quality used in making laminates by low-pressure means is fed into the corrugating machinery. This equipment must be adjusted either to cure the impregnant in the web after which the corrugations are postformed into the web, or so that, during the period of time that the web is between the corrugating mechanism, the resin is fused and then cured. Either of these procedures is satisfactory, but it must be remembered that not all resins will postform. Generally, it will be found that the postforming procedure is faster than the other. Corrugated web cut into convenient lengths is next punched with registering holes, the ridges or crests are coated with an assembly adhesive, and the layers are dropped one on top of another in a restraining jig. After the desired thickness has been built up, the assembly is placed between cauls and put under light pressure to insure contact at the crests until the adhesive is cured. For certain types of impregnants and certain types of combining adhesives it may be necessary to sand the crests of the corrugations before coating with adhesive. After the assembly adhesive is cured the honeycomb is ready for slicing and inspection.

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The Christmas bell or expanded type of honeycomb is easier to register accurately, as the assembly adhesive is applied in stripes across the web by means of a printing machine in such a fashion that its spacing cannot vary. It is then not a difficult problem to locate alternate sheets so that the stripes of the even-numbered sheets fall exactly be-

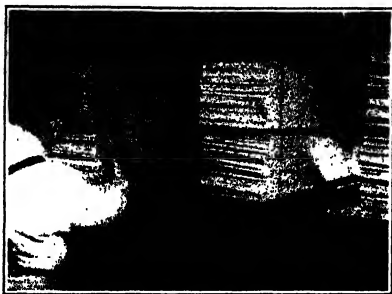


FIG. 22-9. Oven Curing of Assembly Bond of Corrugated-Type Honeycomb Blocks.

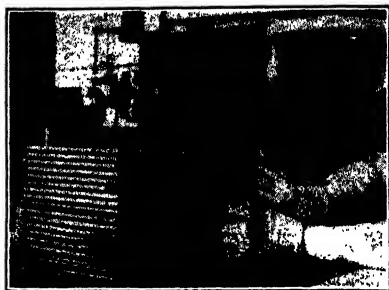


FIG. 22-10. Slicing Honeycomb Blocks into Core Sections.

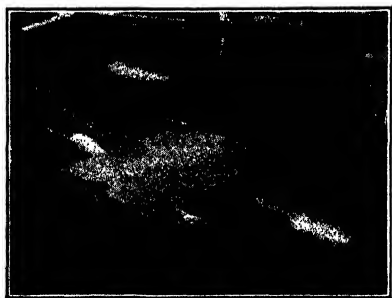


FIG. 22-11. Close-up View of Honeycomb-Core Coating Operation.

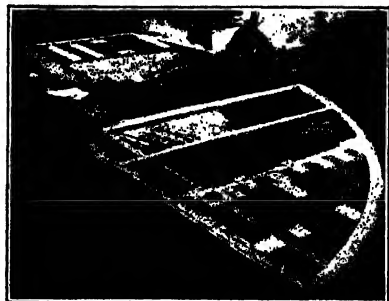


FIG. 22-12. Assembly of a Honeycomb-Cored Sandwich Panel of Intricate Design for Use in Aircraft.

tween the stripes of the odd-numbered sheets. As mentioned before, when a sufficient thickness of the assembly is built up, the whole can be placed under pressure (and heat if necessary) curing the stripe. Obviously a cold-setting adhesive can be used, in which case the assembly or lay-up should be made wet, and the pack should be put under pressure with due observance for the assembly time of the adhesive used. In the expanded-type honeycomb, one can impregnate the web before or after the formation of the honeycomb. If the impregnation is done after expansion, the procedure is obviously one of

lowering the sliced expanded honeycomb on tray-shaped screens into the impregnating bath. This is followed by removal, draining, drying, and curing, which sets the expansion. If the chosen procedure requires the impregnation of the paper or fabric in the web, care must be used in choosing the impregnating resin and the amount used so that the web will not be self-laminating under the conditions of temperature and pressure used to set the striping or assembly adhesive. The only alternative to this requirement, is the tedious one of laying masking strips such as cellophane between each sheet, located so that they will not interfere with attachment at the striped points. The final step in this alternative procedure for expanded honeycomb is, of course, expansion to the desired degree and curing of the impregnating resin, in order to fix the expansion, followed by removal of the masking strips.

Preparation of the metal skins involves cutting to size, inspection for defects, and cleaning. Cleaning cannot be overemphasized. Adequate bonds simply will not be obtained if the metal is not chemically clean on the side to be attached to the core. If the metal is very greasy, it should be solvent-washed or vapor-degreased. If free grease is not present, degreasing may be omitted. In any event the metal must be cleaned in an aqueous alkaline bath of a type recommended by the adhesive supplier for the metal involved. This cleaning should be carried out for the time and at the temperature recommended. Cleaning is followed by a thorough clean-water rinse and must be sufficient to prevent water films from breaking or creeping due to surface tension during draining. This test must always be made, and cleaning must be repeated if perfect water wetting is not obtained. Scrubbing while in the cleaning bath may occasionally be necessary.

For unusually severe services the alkaline bath and rinse may beneficially be followed by an acid bath which generally comprises an appropriate acid, an aliphatic alcohol, and water. Here again the adhesive supplier's instructions should be followed. This is followed by a water rinse and another check for cleanliness and drying. The drying operation is preferably done in a forced circulation of clean warm air. Roller drying and handling with bare hands are to be avoided. Wiping may redeposit grease films. The clean dry metal should be coated immediately with adhesive to prevent collection of grease films from the air.

In either case the cured expanded and sliced honeycomb is, at this point, ready for use in sandwich constructions. The lay-up procedures do not differ greatly from those used in producing end-grain balsa, cellular cellulose acetate, or hard-sponge-rubber cores. For "one-



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step" bonding the appropriate adhesive is necessarily applied to the core and preferably also to the insides of the faces or skins. Likewise, it is necessary to apply the adhesive to the edges of the core sections which adjoin each other and which come in contact with any inserts or edge banding so that proper shear transfer will result. At these points there is a local increase in density which is unavoidable, but, if proper slicing and laminating or pressing techniques are followed, the denser areas will not leave marks, and the bond will be uniform and adequate over the whole panel. There are two precautions to be observed. One of these involves choosing an adhesive for bonding the core to the faces which, owing to surface tension, will build up a little fillet or bead on the edges of the core. Since it is obvious in the case of honeycomb that the point of contact is a narrow line, this must be reinforced by a very strong adhesive which is shock-resistant, craze-free, and will produce a broad bead increasing the area of contact at the point where the skin touches the core. The other precaution to be observed during lay-up, is to crowd slightly the sections of honeycomb so that under pressure they tend to expand, making firm contact between sections and between filler blocks and edge banding.

On completion of the glue application and lay-up, the assembly is bonded in a press. If edge rails and framing are adequate in strength and area to act as stops, pressures normal to plywood manufacture may be used. These are more than adequate to close the press to the rails. If there are no edge bands, the same procedure may be used by placing stops or machined metal bars in the press. An alternate procedure is to press at very low pressures (15 to 30 psi), using a press with special low-pressure controls. The hot press is generally used, as most of the currently available special adhesives adhere best and give the most creep-resistant bonds when cured under combined heat and pressure.

There is, however, a method known as "two-step bonding" which permits the use of the cold press. The metal skins after cleaning are coated with a polyfunctional adhesive just as though they were to be hot-press-bonded to the core. Instead, they are first baked in a circulating-hot-air oven or under radiant-heat lamps until a normal cure is obtained. Then the "primed" skins are cold-bonded, using room-temperature-setting resorcinol-formaldehyde or phenol-resorcinol-formaldehyde resins. Presses in this case are generally screw, fire-hose jig, or cold-baling types.

Faults or defects are unbonded areas, buckled honeycomb, dimpled skins, and panel warping. Unbonded areas are most frequently due to

dirty metal or uneven core thickness. Buckled areas are almost always due to core which was cut too thick but may occasionally be due to excessive pressure which compresses the stops or the edge bands and can result from undercured core. Warping is a fault not easy to analyze, but, if identical faces are used, it should not occur. The best insurance against warping is to make absolutely sure that, the moment the adhesive sets, both faces are at exactly the same temperature.

**Honeycomb Core, Plywood Skin.** Next in popularity to metal-faced honeycomb panels are plywood-faced honeycomb panels. The general construction and procedure for production of plywood-faced honeycomb panels follows very closely that for the metal-faced panels. The skins are generally plywood of the type known during World War II as aircraft grade and consist most often of three plies of very thin veneer such as birch or mahogany. Preparation of core for lay-up does not differ in essentials from that of metal-faced panels, although it may be desirable to use a different edge-gluing adhesive, depending on whether or not hot or cold pressing is contemplated. The cut plywood, of course, must be free of dust, loose particles, or grease, but, generally, the cleaning problem for plywood skins is less serious than that for metal skins. Any burnishing which may have occurred in the hot press during plywood manufacture as a result of excessive pressures, use of caul wax, or use of excessive temperatures may have to be removed by light sanding. If plywood skins are very thin, hot pressing can be used, although it is desirable to use a medium-temperature curing adhesive in order to avoid excessive dry-out of the plywood skins. Cold bonding can, of course, be adopted and will result in panels of high performance and durability with moderate- (room-) temperature-setting phenolic-resin-type resins. For best results it is preferable to coat adhesive on the core and on the inner sides of the plywood faces. It is, however, wise to coat the plywood very lightly and apply most of the adhesive to the core both for economy reasons and in order to save weight. It is not so important to have the plywood skins at identical temperatures at the moment the resin sets, but it is extremely important that they both have the same moisture content. Plywood carelessly handled will produce more trouble with warping than will metal but does not need to do so, and a little forethought will insure gratifyingly flat panels, regardless of size.

**Curved Sandwich Materials.** Curved sandwich constructions are not at present of great importance. During the Second World War they were extremely important, as they were used not only in aircraft construction but also in radomes or radar-antenna covers wherein the

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peculiar properties of the sandwich met the needed requirements of light weight, high strength, and suitable microwave-transmission properties. As might be expected, the procedure for forming curved sandwiches varies with the construction.

Plywood balsa-cored sandwiches are suitable only for simple curves, for, although compound curves could be formed by molding the plywood skins and fitting between them small pieces of cut balsa, the end result would be too costly to be useful. In forming simple curved surfaces, the plywood skins are simply bent to the approximate contour required during lay-up following the procedures outlined for making flat balsa-plywood sandwiches. The assemblies must, of course, be strapped in the curved position until the adhesive has set.

The plastic-laminate skin sponge-core sandwich, so important to radar-antenna covers during the Second World War was produced following procedures exactly as outlined for flat panels using either the one- or the two-step method. The only variation was the obvious one that the core was required to be preformed. The core, after proper heat treating to expel undesirable exudations and to eliminate collapse and explosive expansion, is trimmed to free it from defective sections. Next, it is sliced carefully to correct thickness, and the pieces are placed in a high-temperature hot-air oven in such a manner that they are thoroughly and uniformly heated. Meanwhile, a dummy molding form of the contour desired and composed of some heat-insulating materials such as wood or plastic is prepared. One by one the heated sections of core are removed from the oven and gently but firmly placed in the form in the position they will finally occupy. They are held there for a moment until cool and hard, whereupon they have assumed the curve desired. This procedure is repeated with necessary fitting at the edges until all the core has been shaped and fitted properly in the mold. For the two-step process the core is then removed and placed between the premolded skins after suitable coating with adhesive. For the one-step process the formed core is removed, and the unlaminated but impregnated layers of fabric comprising the outer skin are laid in the mold, the cores are placed on top, and the inner skin assembly is placed in the mold last. It may be observed that this procedure, except for forming the core beforehand, is identical with that of preparing a similar flat panel. Of course, final curing of the assembly is not readily performed in a press but must be done in a unit cooker or a fluid-pressure autoclave, as described earlier in this section.

Metal-faced honeycomb sandwiches are not easily made in either simple or compound curves unless certain expedients are observed, for

it is obvious that, if a true hexagonal honeycomb is bent in a simple curve on one axis, it will attempt to bend in a simple curve in the opposite direction on the opposite axis. If the formation of simple curves is necessary as was the case in radar-antenna housings during the Second World War, limited curvatures can be obtained, provided that the sandwich is relatively thin, and provided, further, that the sections of honeycomb core are kept in rather narrow strips. For thicker sections the only suitable expedient is to make use of relatively small sections of honeycomb for building up the panel. Attachment of skins is best done under fluid pressure, and it will be necessary not only to choose an adhesive that makes an adequate bond under these conditions, but also to make sure that it is well cured. The molding form used must be one which will transmit heat, as it is necessary to apply heat to both sides of the sandwich as nearly simultaneously as possible. Otherwise, the procedure in making metal honeycomb sandwiches which follow simple curves is identical with that for producing flat panels, and the same precautions should be observed.

Compound-curved honeycomb sections have been used only to a very limited extent because of the difficulty and expense involved. The metal skins must, of course, be preformed in either a hydropress or by spinning or by beating or hammering. Special core types have been developed which can be bent in reasonably thin sections in compound curves. They are somewhat higher in weight for a given strength, but they still produce strength-weight ratios superior to more nearly solid core types. Of course, one can always resort to normal types of honeycomb, and the use of rather small blocks in the make-up over areas of severest curvature. A little experimenting with sections of core will soon indicate what can and cannot be done in this direction. Molding, of course, is best performed in an autoclave, or in a unit pressure cooker as it is necessary to force the skins into contact with the core uniformly over the whole area, and to produce heat as nearly simultaneously as possible to both skins.

Compound-curved-plywood honeycomb constructions are not in general use for reasons of complexity of manufacture and cost. Simple curves can, of course, be built up following the procedure outlined for simple-curved-plywood balsa-cored sandwiches. Compound-curved panels could be made by assembling premolded plywood skins, and the procedure is fairly obvious from earlier comments.

It might be well to describe one last method of producing simple- or compound-curved sandwiches which would have undoubtedly become important had the war been prolonged. The construction involved has

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been previously mentioned and includes the forming in place of either hard sponge rubber or foamed synthetic resins between two suitable skins which, broadly speaking, can be either laminates of plastic or plywood or even metal, provided, of course, that the foam can be made to attach itself firmly to the skins and has adhesive properties which develop into a strong bond on curing. It is obvious that a rather complicated tool of considerable strength with accurately spaced walls is necessary, but it is also obvious that the procedure, if justified by a large quantity run, results in a sandwich of extreme accuracy of spacing and in high speed and very reliable production.

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